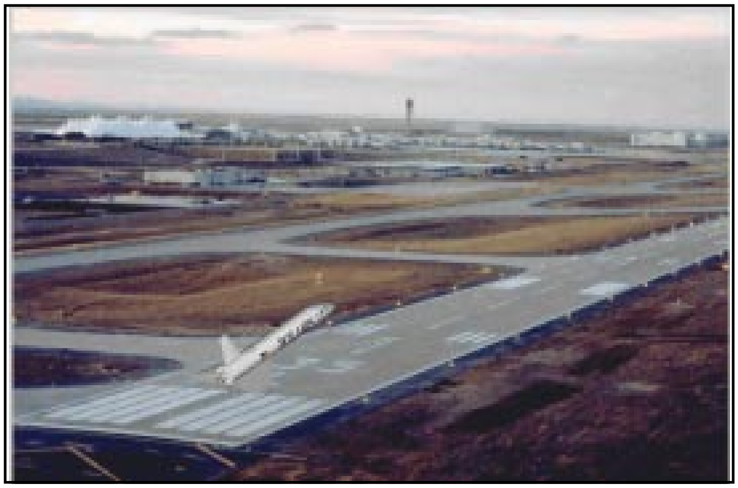
AN OPERATIONAL ASSESSMENT OF CONCEPTS AND TECHNOLOGIES FOR HIGHLY REUSABLE SPACE TRANSPORTATION



Highly Reusable Space Transportation Study
Integration Task Force, Operations

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Johnson Space Center
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PREFACE

The Highly Reusable Space Transportation (HRST) study built on the NASA Access to Space Study and the current Reusable Launch Vehicle (RLV) development effort to explore the possibility of a major reduction in the cost of space transportation. The RLV activity sought to reduce launch costs from $10, 000 to $1000 per pound. The goal of the HRST study was to identify and characterize space transportation concepts, infrastructure and technologies that have the greatest potential for reducing payload delivery cost by another order of magnitude, from $1,000 to $100 per pound. The underlying belief driving this study was that by achieving these cost goals the United States space transportation industry can engender and sustain open-ended space development driven by commercial investments and thus large-scale space transportation market growth.

The NASA Strategic Plan for Human Exploration and Development of Space (HEDS) states that "we will develop revolutionary, new advanced transportation concepts and demonstrate advanced propulsion systems to enable exploration". In conformance with this charge, Phase I of the HRST study consisted of preliminary concept studies, assessments and analysis tool development for advanced space transportation systems. Phase II included end-to-end system concept definitions and trade analyses, specific system concept definition and analysis, specific key technology and topic analysis, system, operational and economics model development, analysis, and integrated assessments. The HRST Integration Task Force (HITF) was formed to complete the HRST study as part of the final phase. The HITF was to synthesize study results in several specific topic areas and support the development of conclusions from the study. In order to accomplish this task, the HITF was to conduct detailed studies and critical experiments for selected options.

The HITF effort was divided into four major areas of investigation:

- Systems Concepts Definitions
- Technology Assessment
- Operations Assessment
- Cost Assessment

Four teams were formed and each assigned one of these areas in which to conduct assessments. Integration of results was to be pursued across the above four areas, including development of high level metrics for assessing the promise of particular concepts in achieving HRST goals and objectives. The Systems Concepts Team was assigned the task of integrating the results of each of the teams.

This report is a product of the HRST Integration Task Force, Operations (Ops Team.) The HRST Study Manager chartered this Government-only team to:

- Assess the various HRST concepts for their relative operational effectiveness
- Characterize anticipated operations parameters
- Identify systems and concepts that show two orders of magnitude improvement over current operations
- Identify technology areas in the context of proposed system architectures that enable HRST-class operation

- Provide recommendations to the Study Manager for follow-on activity.

The current study focuses on identifying launch system architectures and technologies that can enable attainment of significantly lower payload delivery costs. By identifying the most promising developmental paths towards more cost-effective operations, the Operations Integration Team hopes to make the goal of order-of-magnitude lower launch costs more attainable.

An over view of the HRST study results appeared in the March 1998 issue of *Aerospace America* in an article "Lower Costs for Highly Reusable Space Vehicles", by John C. Mankins, NASA Headquarters.

Mike Nix
Co-Lead
Highly Reusable Space Transportation
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CONCEPTS SELECTED FOR DETAILED ASSESSMENT

Five strategic lines of investigation were followed: Combination propulsion systems (CPS); combined cycle propulsion (CCP); Launch assist (use of off-board energy); Revolutionary (on-board) propulsion systems; and highly evolved expendable vehicles (HEELV's). The various teams also investigated the cross cutting topics of operations, manufacturing, and thrust augmentation and upper stages as applied to the goal of reducing launch costs.

Various contractor, academic and Government teams developed eighteen vehicle concepts in Phases 1 and 2 of the HRST study. The HRST Study Manager and the HITF team leads as a group selected nine of the space transportation vehicle concepts for in-depth assessment as appropriate representatives of the major families of vehicles. The criteria used for selection was (1) concepts most likely to have sufficiently detailed data available to support the integration work and (2) concepts representative of vehicle "families" (see below). The concepts selected are listed below. For convenience, the concepts will be generally referred to in the report by the common name as indicated in **bold**.

1. Vertical Take-off, Vertical Landing (VTVL) Supercharged Ejector Scramjet (SESJ) Single-Stage-to-Orbit (SSTO) .
   - Developer: Kaiser Marquardt (with Georgia Tech.)
   - Common name used for concept: **Kaiser Marquardt or KM**

2. Horizontal Take-off, Horizontal Landing (HTHL) Supercharged Ejector Ramjet (SERJ) Non-waverider Type Single-Stage with Launch Assist.
   - Developer: Georgia Tech Aerospace Engineering, “Argus”
   - Common name used for concept: **Argus**

3. Horizontal Take-off, Horizontal Landing (HTHL) Rocket Based Combined Cycle (RBCC) Waverider Type Single-Stage with Launch Assist.
   - Developer: Boeing North American (BNA)
   - Common name used for concept: **Waverider**

4. Rocket, Baseline Comparative System Update, Using Advanced Chemical Rocket Engine (T/W engine = 92).

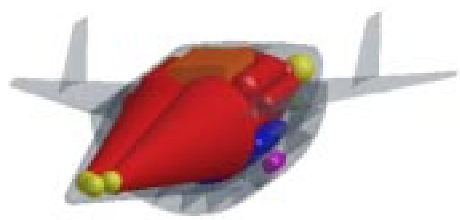
- Developer: Boeing North American (BNA) – Rocketdyne
- Common name used for concept: **ACRE 92**

5. Rocket, Baseline Comparative System Update, using Advanced Chemical Rocket Engine & New Materials (T/W engine = 183).

- Developer: Boeing North American - Rocketdyne
- Common name used for concept: **ACRE 183**

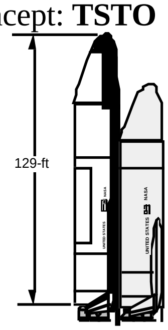
6. Horizontal Take-off, Horizontal Landing (HTHL) Ejector Scramjet (ESJ) Single-Stage-to-Orbit (SSTO).

- Developer: Georgia Tech Aerospace Engineering, "Hyperion"
- Common name used for concept: **Hyperion**



7. Two-Stage to Orbit (TSTO), Vertical Take-off, Horizontal Landing (VTHL) All Rocket (Reusable Booster & Orbiter).

- Developer: Langley Research Center TSTO, Vehicle Analysis Branch
- Common name used for concept: **TSTO**



8. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit Liquid Air Collection and Enrichment "LACE" Ejector Ramjet/Scramjet

- Developer: Langley Research Center SSTO, Vehicle Analysis Branch
- Common name used for concept: **LACE**

9. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit All Rocket with Launch Assist

- Developer: Space America, Inc.
- Common name used for concept: **SSTO(R) LA**

Note: This concept was introduced late in the integration activity and was evaluated only with COMET/OCM and PrOpHET.

These concepts are described in detail in Appendix B except for SSTO(R) LA.

INTEGRATION TASK FORCE, OPERATIONS

Various documents used in production of this report may be found at NASA's Virtual Research Center Internet location at http://moonbase.msfc.nasa.gov in the Operability Wing. Most documents are available through Public Access. A request for badged access may be submitted through the web site.

The specific objectives of the HRST Integration Task Force, Operations (hereafter, Ops Team) as tasked by the HRST Study Manager were:

- Define and assess operations scenarios and sensitivities required for various HRST concepts.
- Use analysis tools to conduct actual simulations of operations scenarios, including relative operations costs.

In pursuit of these objectives, the Ops Team was to examine potential families of HRST vehicles to include:

- All-rocket types (Two-Stage-to-Orbit (TSTO) and highly advanced Single Stage to Orbit (SSTO)).
- Combination Propulsion (Mach 6 and Mach 10) types.
- Combined Cycle Propulsion (Mach 6, Mach 12 and Mach 15) types.

Very advanced concepts (fusion and off-board-beamed power) were not included due to the lack of information at a level of detail needed to support the integration effort.

The Os Team was to use several data sources such as Technology Interchange Meeting (TIM) results and pertinent literature. In addition, various data acquisitions work sheets were developed and distributed to the concept developers to supplement information from TIM presentations.

In general, the goal of the HRST study was to determine if there were space transportation system concepts and technologies with the potential to reduce total recurring operations cost per launched unit payload mass to $200 or less per pound to low Earth orbit (LEO - 100 nautical miles circular orbit at 28.5 degrees inclination.) For the purposes of this assessment, this amount was to include all recurring costs except those that are not technical in nature e.g., cost of financing, etc.

APPROACH

The Ops Team determined that the assessment could best be done as follows:

- Develop the appropriate criteria by which the potential of the HRST vehicle concepts to achieve the recurring cost and price goals could be assessed.
- Select or develop analytical/assessment tools and/or techniques that support the criteria.
- Conduct assessments using the tools and techniques selected.
- Perform reviews within the team.
- Provide draft findings to Other Assessment teams and concept developers for comment.
- Finalize the Ops Team report.

The following issues in assessing the concepts were recognized and considered by the Ops Team:

- There was little detailed data on the concepts at this stage of concept exploration in the area of operations.
- The level of detail in information about concepts varied widely across the concepts. In general, all-rocket concepts with relatively little technological advancement in development and operations had more detail and less uncertainty than air-breather concepts with considerable technology development required and practically no operations experience. This disparity gave rise to the formidable problem of avoiding “penalizing” concepts in the assessment because there was much data, some of which might indicate low probability of achieving the HRST study goals or because there was too little data available to support the tools or techniques used in the assessment
- Some of the data was considered proprietary by the developers.
- There are few operational analysis tools suitable for this early phase in concept exploration, especially in view of the level of detail and confidence in the data available.

Multiple approaches and analysis tools as outlined in the next section "Operations Integration Analysis Tools" were used to gain insight into the broad technology, concept specific and economic factors associated with the objectives of the HRST project. More importantly, the multiple approaches facilitated insight into the interaction of all of these factors.

OPERATIONS INTEGRATION ANALYSIS TOOLS

The Ops Team, confronted with a scarcity of operations and operability analysis tools suitable for use at this early stage of concept development, developed new tools and procedures for this assessment effort. Six operations analysis tools/techniques, of which four were developed by various members of the Ops Team for the HITF activity, were used in assessing the potential of the nine concepts to achieve low cost operations. This varied approach was selected for the following reasons:

- To take maximum advantage of the wide range of skill and experience available in the Ops Team.
- To overcome the variance in the level of detail in concept data described above.
- To cope with the degree of uncertainty inherent in data at this stage of concept development. This aspect is discussed in more detail below.
- By approaching the operations analysis in these different ways, it was anticipated that the concepts most appropriate for further study would manifest themselves through convergence in the results of the six analysis methods.

The issue of uncertainty was a major consideration in the assessment effort. The goal of any modeling activity is to accomplish accurate quantification in as realistic an environment as possible. This involves the need for quantifying in the presence of uncertainty. Uncertainty is not only reflected in the accuracy of the information that exists, but also in the availability of information that may lead to an inability to accurately model the system. Both of these instances lead to the difficulty in the presentation and interpretation of "point estimates" or single quantitative measures reflecting the comparative value of the concept. Uncertainty present in concept definition and available concept data implies the need to present not only quantitative estimates of central tendency (mean, median, etc.) but also of dispersion (standard deviation, variation, etc.).

With advanced concepts and limited data, a relative range of possible results may be the most appropriate result. Such a range may be derived from varying assumptions and new model runs with worst-case and best-case scenarios. This often involves sensitivity studies of the concept models by varying inputs to key parameters. One concept may provide a higher payoff but may be subject to larger variation, thus making it a much riskier venture. One concept may show a benefit over another in one scenario and just the opposite in a second, equally plausible, scenario. Thus, any decisions that result from analysis of this type should consider uncertainty. In this regard, there was no way at this point in the HRST study to decrease either the variance in level of detail across concepts or the uncertainty present in the data. By taking the different analysis approaches discussed below, the Ops Team hoped to alleviate in part the effect of uncertainty on the validity of the results. Convergence in terms of which concepts consistently proved potentially superior as determined across all or most analyses would tend to indicate that those concepts were most likely embued with more desirable operability characteristics.

Nonetheless, the analysis methods, qualitative or quantitative, reported in this document do present point estimates as results. Further analyses of the concepts in follow-on work should proceed toward the goal of characterizing the uncertainty inherent in the data and the concepts and reflecting that in the "measures of merit" selected.

The operations assessments were conducted using constraints and requirements defined in "Highly Reusable Space Transportation, an Advanced Concepts Study Project Study Guidelines" (September 5, 1995). Those pertinent to operations are included as Appendix A.

These six operations analysis tools/techniques are introduced here and described in detail in Appendices C through H of this report.

1) Based on the work of the Space Propulsion Synergy Team (SPST) done in support of the HRST study, a qualitative, relative assessment of the HRST concepts was performed. The SPST is a broad, diverse group comprised of members of industry, NASA and academia with relevant backgrounds in space propulsion and transportation. The joint effort performed in support of the HRST study was documented as "A Guide for the Design of Highly Reusable Space Transportation". This SPST process developed criteria traceable to national policy and the goal of affordable access to space enabling commercialization. Edgar Zapata, KSC used a matrix of the criteria outlined in this document to evaluate each concept. Measurable criteria for both benefit and programmatic factors were available. The benefit assessment encompassed features of a design as related to safety, responsiveness, reliability, operability, dependability and so forth (i.e. payoff and recurring costs). The programmatic assessment encompassed features of a design as related to costs, schedule and risk in R&D as well as acquisition (i.e. non-recurring costs). The review was performed by KSC based on the results and criteria established by the SPST. (For a full description see Appendix C)

2) The earlier HRST study effort also included the development of the Operations Simulation and Analysis Modeling System (OSAMS). OSAMS is a systems analysis tool intended to allow program managers and developers to quickly assess the most effective areas to invest scarce resources and evaluate the potential impacts of these investments on the "life-cycle" and per mission cost of the system. OSAMS is intended to provide a unbiased and consistent means to evaluate competing alternative launch and operations concepts, evaluate the impact of proposed technologies, and provide insight into life cycle, development and operations costs. An additional model was used in conjunction with OSAMS: The Operations Cost Model (OCM) developed at MSFC in April 1994 by General Dynamics Space Division. This is a top-level tool for modeling launch and flight operations costs for space transportation systems. OCM consists of two modules, OCM and the Conceptual Operations Manpower Estimating Tool (COMET.) (For a full description see Appendix D)

3) Another SPST - HRST Support Group effort, headed by Carey McCleskey and Russel Rhodes of KSC, in support of the HRST study, developed the "Architectural Assessment Tool" (AAT). The AAT is a means for scoring and ranking concepts for operational effectiveness as well as assessing the programmatic factors involved with research & technology and commercial acquisition. This tool uses quantitative techniques in a qualitative process to gain investment insight at the architectural level. This tool was developed recognizing the lack of information on design and operations available during the early concept phase. (For a full description see Appendix E.)

4) A maintenance operations analysis tool developed by Doug Morris and Nancy White, LaRC, the Reliability Maintainability Analysis Tool (RMAT), defines Reliability and Maintainability (R&M) characterization of new launch vehicles in the early pre-concept and concept exploration phases. Other than engineering judgment, no alternative exists for defining the R&M characteristics at this level of study. RMAT is based on comparability to aircraft and Shuttle R&M characteristics for similar systems and is driven by the vehicle description in terms of weight, dimensions and other system specific variables. The R&M

results can be used to estimate, at top level, the support requirements of advanced concepts. For this study the model was used to define the R&M improvements required of new technologies to meet the stated CAN support and flight rate levels. (For a full description see Appendix F.)

5) Richard Brown, MSFC, used a hierarchical analysis method, developed by Dr. Thomas L. Saaty. This method is used for decision analysis where a deterministic solution is not possible, and decisions are based on pair-wise comparisons of alternatives relative to the criteria that measure success program. (For a full description see Appendix G)

6) John Mankins, HRST Study Manager, suggested the possibility that the Operations and Maintenance (O&M) burden, expressed as hours of O&M required per pound of subsystem dry mass per flight, could be based on dry weight of subsystems. An Excel spreadsheet model, the Parametric Operations & Maintenance Hours Estimating Tool (PrOpHET) was developed by Mike Nix, MSFC, to implement this approach. (For a full description see Appendix H)

DISCUSSION AND CONCLUSIONS

In general, rocket based combined cycle (RBCC) concepts appear to have significantly greater **potential** than all-rocket concepts for reducing operations costs. Not all of the RBCC vehicles clearly exhibited this greater potential, but the majority of the RBCC concepts did.

RBCC propulsion offers significant near term potential toward achieving HRST objectives of cheap access to space at $100 to $200/lb. of payload. The RBCC concepts, with margin gains considered to have a distinct tie in to potential operability gains, have a notably higher benefit over all-rocket concepts. However, this occurs for concepts focused more squarely on operations as a driver.

Margin that does not translate into operability does not offer significant improvement over current systems regarding lower cost operations. Not all airbreather concepts ranked equally. This is likely due to differences in the design focus around multiple variables. Margin as evidenced by required mass fractions twice or three times lower (better) than a rocket single-stage-to-orbit is considered relevant only if it translates into operability or payload with operability as more crucial. The potential of airbreathers is not likely to be demonstrated immediately in any attempt to gain significant payload combined with test and demonstration. It is more likely that as the technology evolves, if properly focused on recurring costs, capabilities beyond rocket reusable launch vehicles will be achieved in payload cost per pound and payload per year in the long term due to recurring cost improvements.

Actual flight rate capability for any of the concepts considered is a crucial determinant in overall affordability. It is believed basic concept decisions deterministically constrain flight rate capability and associated infrastructure. This determines productivity. (For further discussion, see Appendix E.) Predicting what this capability is, based on conceptual information has multiple uncertainties. The capability is mostly determined by these up front design decisions, but not necessarily known. Methods used in this assessment attempted to determine the actual likelihood for a concept to avoid the Shuttle scenario, a low single vehicle flight rate capability with high infrastructure requirements per vehicle. The Architectural Assessment Tool (Appendix E) and the design criteria assessment (Appendix C) used inherent design features unrelated to weight to assess probable productive capability such as flight rate at a given manpower and operating cost. It is stressed here that this actual flight rate can make or break the ability of a concept to even approximate HRST goals. For this reason, further definition on the few concepts considered most likely to achieve HRST goals is required to fully develop any research and technology portfolio. Many of the concepts can be discarded based on the assessments already made as having flaws preventing attainment of HRST goals. Certainty on the remaining concepts requires further iteration.

Reliability is a major factor in any concepts achieving HRST goals. Technology maturity to a level that is similar to commercial off the shelf items such as in aircraft can only come about with large production capabilities. The well known "chicken and egg" scenario can be improved upon by proper feed-through of requirements into the design, test and certification processes. R&T that neglects this, as when driven solely by up-front cost and schedule, is essentially creating downstream costs in operations which eliminate the possibility of achieving HRST goals. It is further believed that approaches in development can negatively affect technology maturity such as through emphasis at sub-system levels when actual problem causes are at higher system levels.

The recurring cost impacts of launch assist require further understanding and quantification. The concept ranked with the most benefit is the Horizontal-take-off-Horizontal-Landing (HTHL) single-stage Supercharged Ejector Ramjet (SERJ) with launch assist (Argus). This estimate is more uncertain given the lack of an operational database or group of expertise related to such a system; this uncertainty is in addition to and larger than uncertainties on propulsion. Studies on similar systems can assist in definition at the component level of similarity. Passenger rail systems are not applicable in the following areas of experience:

- With cryogenic fluid interfaces to or through a sled (versus electrical power distribution only),
- The dynamics of separation (versus transient fixed systems),
- The speeds at the high end for these concepts,
- The load distributions and the complexities of the sled itself (pitch up actuators, interfaces - fluid, electrical and structural).

Complexities here are more similar to staged space transportation systems.

Launch assist where used to simplify a system, especially the vehicle, meant greater benefit moving toward HRST goals. Where launch assist was used to reduce mass fraction or in combination with more systems, it resulted in little benefit over rocket systems. Of the two concepts incorporating launch assist, Argus ranked significantly better than Waverider on benefit and slightly better on R&D programmatics.

Optimizing launch vehicle concepts at the system level rather than optimizing components is more likely to result in recurring costs in the range of HRST goals. There are technologies that reduce the operations and maintenance (O&M) burden that are common to both all-rocket and airbreather type concepts. For the HRST concepts examined in detail using RMAT (Figure 10), the major driver of maintenance burden was the TPS system, representing from 55 to 83 percent of the total burden. Structures, Main Engines, and MPS are generally the next major contributors, the order depending on the concept. The potentially large recurring economic impact of closed compartments on cryogenic vehicles should not be underestimated. Future system features such as purged aeroshells, TPS purges, multiple separate tanks in order to conform to certain moldline approaches, and multiple engine modules should not be underestimated in the degree to which the resulting required infrastructure can be non-responsive to lower operations cost goals. Numbers of interfaces, numbers of active systems required to operate safely, numbers of strict requirements on flow rates and temperatures, numbers of detection systems and measurements, and numbers of failure modes or opportunities for failure are all negatively affected by these types of approaches.

The following technology areas were identified by the operations team as having higher priority for development because they offer the potential for most significant reductions in the O&M burden, both taken individually and in combination at the systems level. In order of most significant impact on operations:

> **Packaging and Integration:** The concepts reviewed, although integrating the rocket and airbreather in RBCC type concepts, did not integrate the secondary and main propulsion systems. Rocket systems with orbital maneuvering, reaction control and main propulsion systems are highly non-integrated. Future

developments must more readily address propulsion technology integration that reduces interfaces, separate tanks, etc.

TPS development without aeroshells & purges: The development of passive, robust, zero-coating, zero-waterproof, zero-purge TPS is a top priority for reducing recurring costs.

Number of Engines: Engine count is a key, simple measure of potential benefit. Development focus should be on fewer engines. Objectives should be between 2 and 4 main engines or engine modules. Fewer engines relates to multiple measures of benefit such as reducing confined spaces, which inherently require purges, servicing and interfaces to the ground, as well as additional complex systems for leak detection and isolation. Engine count also relates to key issues of additional interfaces (flight and ground, fluid and electrical), basic issues of reliability and dependability (more parts, more opportunities for failure, and more maintenance), active systems, and functional complexity (flight and ground).

Reliability & Dependability: Hardware and system reliability and dependability are keys to low cost operations. In order for a space transportation system to meet the HRST goals of hundreds rather than thousands of dollars per pound, very high degrees of dependability must be achieved. Hardware replacement costs must be a small fraction of a percent per flight, keeping the vehicle out of the hangar, increasing its commercial utilization, i.e., flight rate, which is a highly critical parameter for commercially viable space transportation.

Commercial-Off-The-Shelf (COTS): A key to reducing recurring costs is maximum use of COTS products. Many subsystems currently used in space transportation systems will require intensive research and development and DDT&E programs in order for the majority of components and software to become commercially available. Yet, this is a must for attaining the order-of-magnitude operations cost reduction. (For a detailed discussion, see Appendix E.)

Vehicle Health Monitoring (VHM): The continued development of Vehicle Health Management (VHM) technologies is also required to enable achievement of lower operations costs. Critical in this area is the non-intrusive detection of fluid leakage and other techniques to overcome the tremendous amount of unplanned maintenance that occurs between flights of functionally complex vehicles, such as a reusable launch vehicle - particularly a highly reusable launch vehicle.

Horizontal vs. Vertical take-off: The benefit of reduced infrastructure for vertical landing may represent a far term capability that is desirable for operating within infrastructure or location constraints. Aircraft, for example, have evolved both large passenger jets as well as urban centered helicopter services. For the near term, however, the ability to simplify space transportation as far as relates to engine count will be assisted uniquely by horizontal take-off. Assuming engine out requirements, the horizontal take-off uniquely allows both low engine count as well as ease of recovery and return to the spaceport. This is an area where rockets have no potential for improvement, with high engine counts required for engine out capabilities. Further, horizontal take-off rockets, especially single stages, are practically constrained leaving vertical take-off options as most viable, which again entails high engine counts.

Environmentally benign technologies: Ground-rules for future system development should include no hypergols (propulsion or power) and avoidance of multiple toxic freons and ammonia. Based on Shuttle experience, these relate directly to high operating costs, hazards and complex servicing, and turnaround requirements.

Avoidance of slush hydrogen: Slush hydrogen introduces unfavorable programmatic (non-recurring cost) impacts as well as unfavorable benefit (recurring cost) impacts. Use of slush hydrogen is not conducive to the use of facilities and infrastructure that are simple and responsive to high flight rates.

Hydrogen as common fuel: Advances in non-rocket areas may benefit the ability to use hydrogen as a common fuel in systems such as the Hyperion HTHL SSTO turbofans (used for loiter and self ferry). This would eliminate separate JP fuel, possibly simplifying servicing, basic design and operation. This represents an avenue of future study to determine synergy potential with other work in Hydrogen energy applications.

Additions of complexity must be further quantified as to benefits. The addition of systems such as fans, liquid air collection and enrichment (LACE), slush hydrogen and launch assist did not always mean greater recurring benefit in the Ops Team analyses. Neither did additions of complexity, adding capabilities such as loiter, thus eliminating a dead-stick glide-in landing, necessarily result in less recurring benefit As an example of this, Argus uses a fan / supercharging approach. The benefits to be accrued from these additions were highly dependent on overall system configurations, how they are integrated into the whole concept and against what they trade. It is highly possible to have increasing complexity coupled with increasing economic viability as witnessed in today's aircraft and airport infrastructures that are many orders of magnitude more complex than early aircraft in the pre-DC-3 era. It is clear from the example of the Concorde airliner that there is also a threshold at which increasing complexity ceases to provide commercially effective benefit. Heretofore space transportation systems, having to operate at the edge of performance by their very nature, had to be very complex without commensurate operational effectiveness. The concept that integrates increasing complexity toward low cost operations is crucial to basic airbreather economic viability.

Room for improvement exists. The Ops Team developed a conceptual vehicle that embodies the systems optimization approach for operational effectiveness. An ideal spaceliner, Horizon Mission, described in Appendix C, and appearing on some of the Figures below, is an even more dramatic improvement over the systems conceptualized for this study. Iteration toward this improvement is possible with existing concepts.

Figures 1 and 1.a show how the concepts were ranked in order of preference by each analytical approach. As discussed above, the approaches were deliberately varied in measures of merit and procedure to compensate for the uncertainty inherent in operations data in this early phase of concept exploration. There was general agreement in the results. Argus, an SSTO HTHL RBCC vehicle with Launch Assist, appears eight times in the top three ranks, six times as the top ranked concept. The all-rocket SSTO HTHL ACRE 183 appears five times. While Hyperion (HTHL SSTO RBCC) appears four times, this overall rating was discounted because of the low payload capability (20K). Kaiser Marquardt's VTVL SSTO RBCC appears 3 times while the HTHL RBCC SSTO Waverider, also with Launch Assist appears twice. ACRE 92 and the TSTO VTHL all-rocket appear once each. From these rankings, it seems clear that RBCC type vehicles can offer operational advantages. That not all do may be traced to additional system complexity that does not increase operability proportionally. Rockets with advanced materials (lightweight, low maintenance) have some potential of achieving HRST low operations cost goals. Launch assist does not appear to confer a particularly decisive advantage, as witnessed by the difference between Argus and Waverider rankings.

Concept Name	Number of Times Ranked in Top 3 by Analysis
Argus	8
ACRE 183	5
Hyperion	4
KM	3
Waverider	2
ACRE 92	1
TSTO	1
ANSER	0
LACE	0
SSTO(R) LA	0

Figure 1: Number of Times Concepts Were Ranked Among Top 3 by the 8 Analytical Measures

Analysis Approach →	Design Guide	AAT	COMET/ OCM	PrOpHET			RMAT	AHP
Measure of Merit →	Operational Benefit	Operational Effectiveness	Operations Headcount, Annual $, $/Flight	O&M Hours/ Flight	O&M Hours/ Flight/ Mass Fraction	O&M Hours/ Flight/ Lb Payload	Maintenence Burden (Hours)	AHP Scores
Higher Rank	Argus	Argus	Hyperion	Argus	Argus	Argus	TSTO	Argus
	Hyperion	KM	Argus	Hyperion	Hyperion	ACRE 183	Argus	KM
	KM	ACRE 183	Acre 183	ACRE 183	Waverider	ACRE 92	ACRE 183	Waverider
	Waverider	Hyperion	Acre 192	ACRE 92	KM	SSTO(R) LA	Hyperion	ACRE 92
	LACE	Waverider	Waverider	SSTO(R) LA	ANSER	Waverider	LACE	ACRE 183
	ACRE 183	LACE	SSTO(R) LA	Waverider	LACE	KM	*	TSTO
	ACRE 92	TSTO	KM	KM	SSTO(R) LA	ANSER	*	LACE
	*	*	LACE	ANSER	ACRE 183	LACE	*	*
↓	*	*	*	LACE	ACRE 92	Hyperion	*	*
Lower Rank	*	*	*	TSTO	TSTO	TSTO	*	*

Figure 1.a: Summary of Concepts Rankings by Analytical Approach

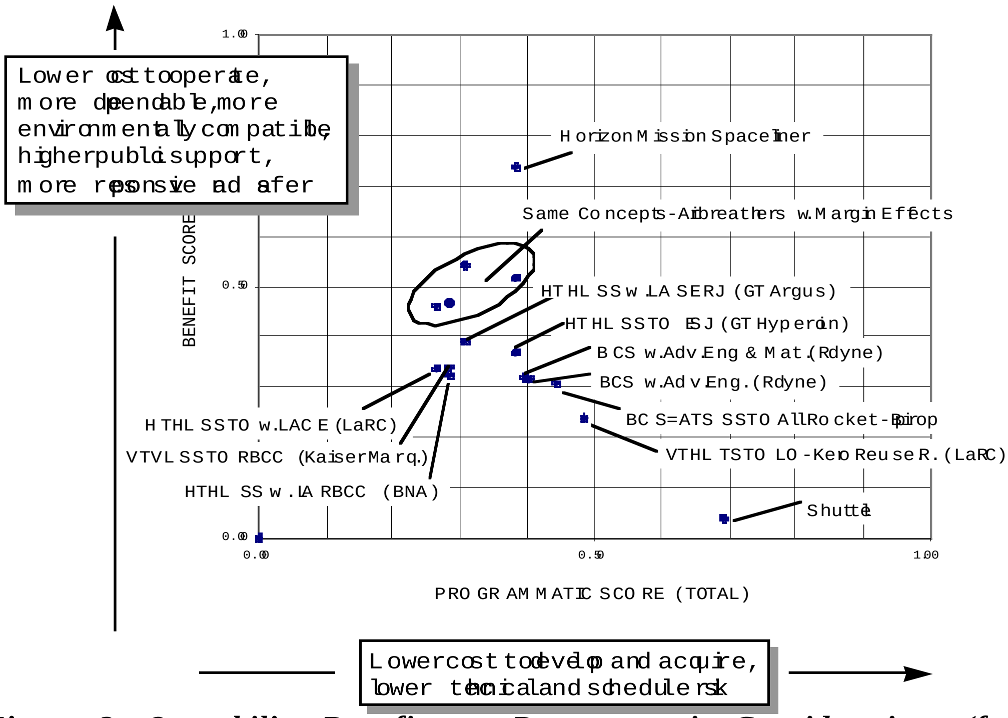


Figure 2: Operability Benefits vs. Programmatic Considerations (from the "Guide")

Figure 2 indicates the ranking of concepts in terms of operational benefits and programmatic considerations from the "Guide". The higher the placement on the chart, the greater are the benefits (lower cost, greater dependability, more responsiveness, etc.). The further right the placement, the lower are the development cost and risk. Airbreather types tend to place higher than all-rocket types but somewhat to the left. The conclusion is that airbreathers in general offer potential for greater operational benefits but require more development and incur higher risk to achieve them. The concepts encircled are the same airbreathers with margin applied to the enhancement of "operability." Note that these move up (greater operational benefit) but neither left nor right (same cost and risk.)

Figure 3 (below) is derived from the AAT assessment and, scaled as in Figure 1, indicates that RBCC type vehicles (in general, but not all) offer greater operational effectiveness than all-rocket concepts. Note that ACRE 183 competes well with RBCC's in this analysis. The horizontal scale of Commercial Acquisition places the concepts in terms of relative commercial viability. The figure further indicates that operational effectiveness can be increased for all concepts by applying Design Principles from the "Guide and Rules of Thumb (for applying margin to enhance operability) developed by the Ops Team.

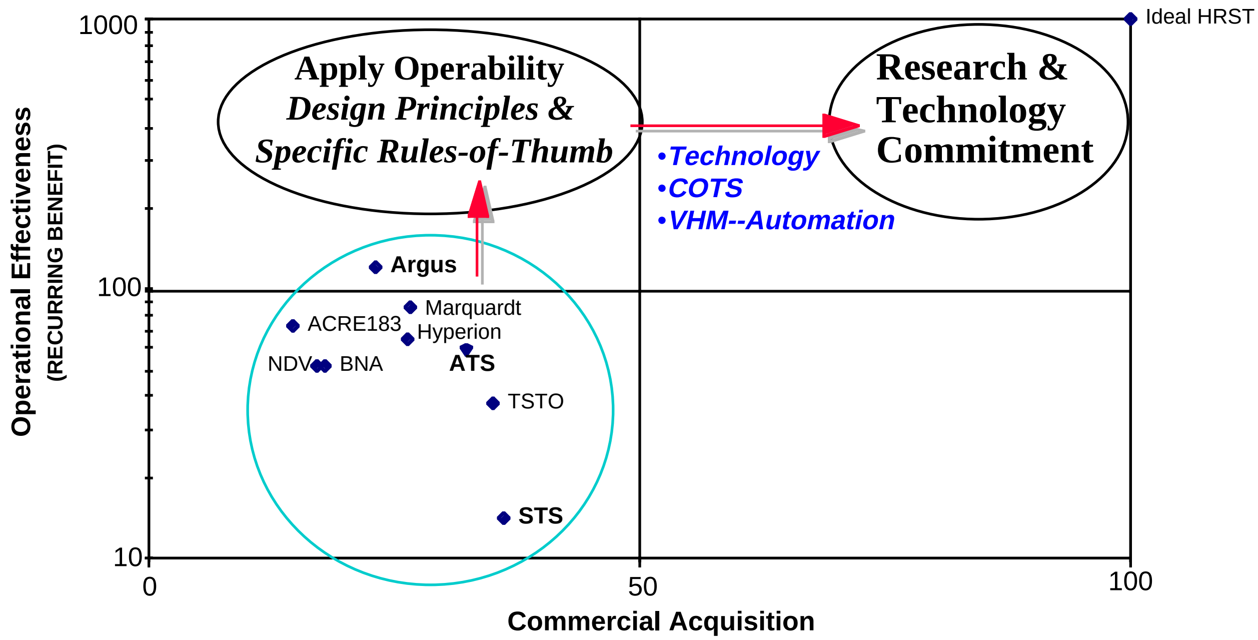


Figure 3: Operational Effectiveness vs. Non-Recurring Investment Commitment (from AAT)

Figure 4 indicates the AAT scores for the concepts (relative ranking) as well as the potential flight rates (per year per vehicle) enabled by the concept architectures. Figure 4 also indicates the relative number of O&M hours per flight per lb. of dry mass, which were used in the PrOpHET analysis.

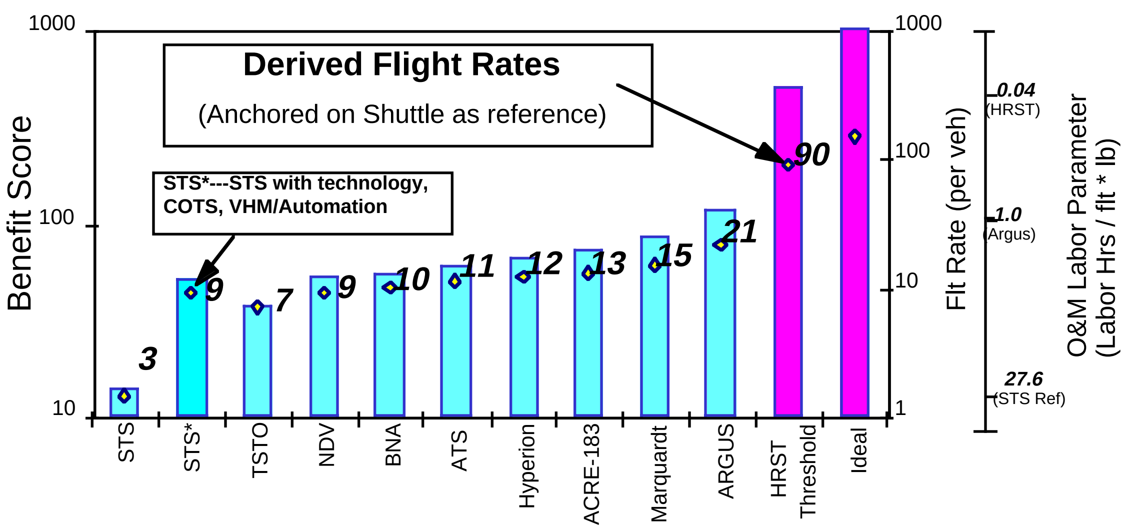
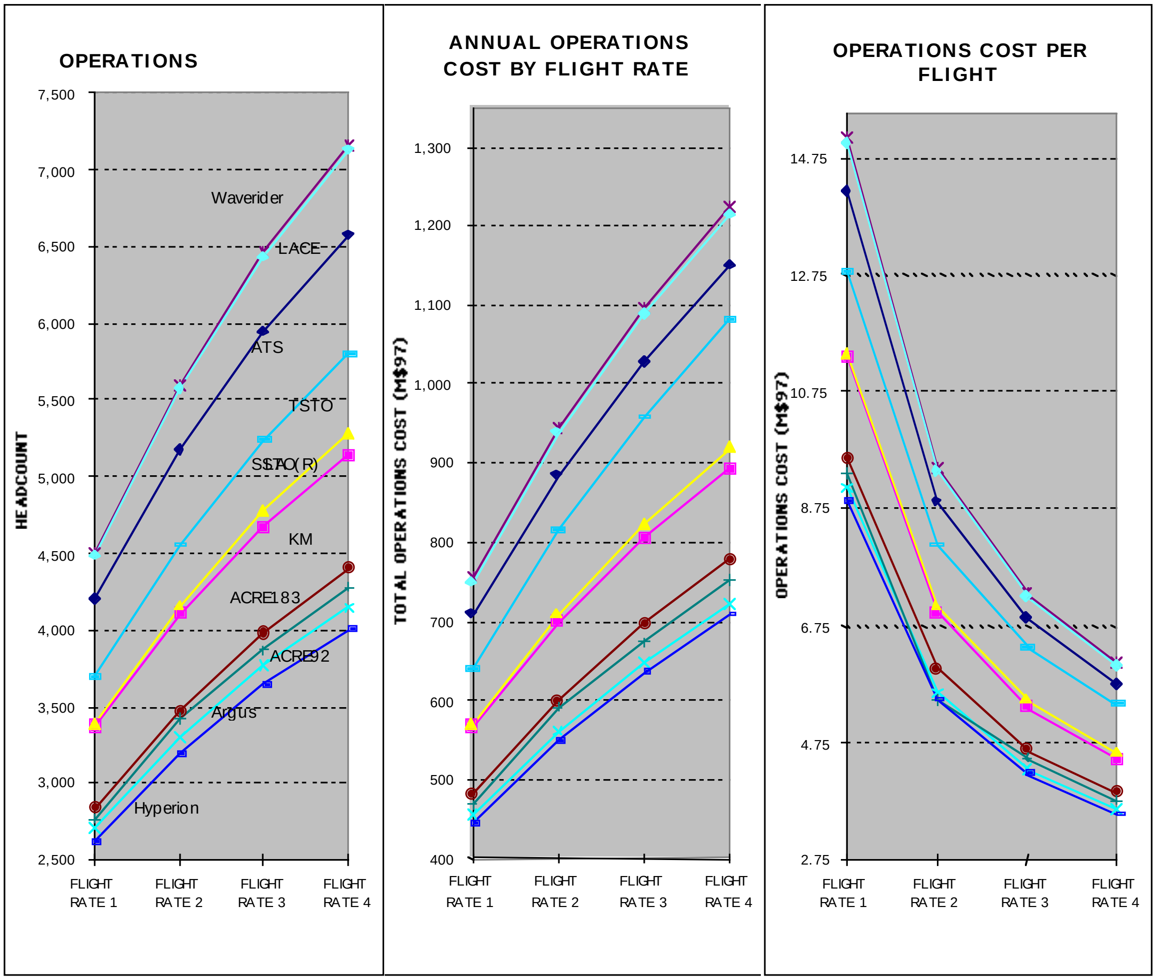


Figure 4: Single Vehicle Utilization Assessment (from AAT)

Figure 5 shows the COMET/OCM results for headcounts required for launch and flight operations and support functions, encompassing the entire launch site for rates of 50, 100, 150 and 200 flights per year. Argus, Hyperion and the two ACRE's, by COMET/OCM analysis, require the lowest number of personnel to operate the launch site (and the lowest annual costs and cost per flight.) The All-Rocket SSTO with Launch Assist (a late addition to the assessment effort that was analyzed only with COMET/ OCM and PrOpHET) compared well as did the Kaiser Marquardt concept. The LACE and Waverider RBCC concepts required the greatest processing staff levels, driven primarily by engine and TPS subsystem complexities and complexity of mission profile.



Note: Flight Rates 1 through 4 shown are 50, 100, 150 and 200 flights per year

Figure 5 Operations Headcount, Annual Cost and Cost by Flight (from COMET/OCM)

Figure 6 indicates the relative headcount requirements for launch (gray bars) and flight operations (black bars), including support functions, for four flight rates, a breakout of the numbers form the headcount portion of Figure 5. Figures 5 and 6 indicated some variance in sensitivity to flight rates among the concepts. Note that the ratio of flight operations to launch operations headcounts is not constant across the concepts in Figure 6. This results from variation in the mission complexity, which is driven in large measure by the complexity of the concept architecture. An advantage in operability goes to some of the RBCC's and either the advanced rocket concepts or the rocket with launch assist. Again, launch assist did not confer a decisive advantage to a concept.

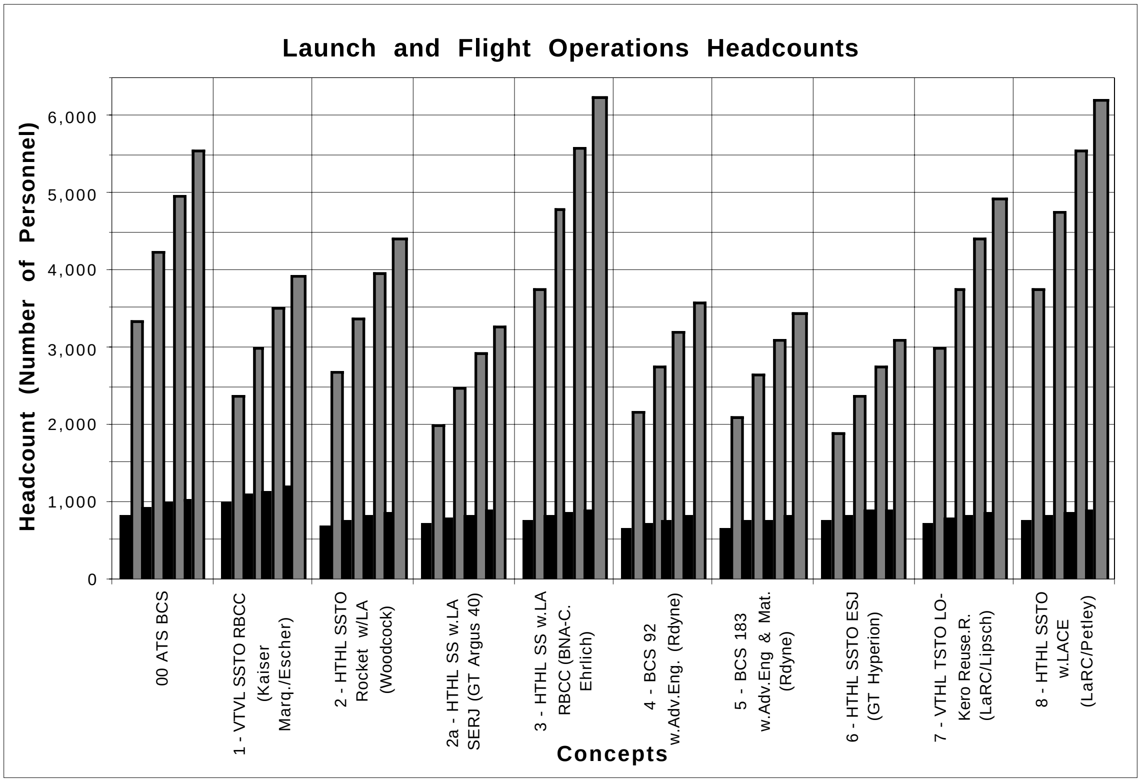


Figure 6: Launch and Flight Operations Headcounts for Flight Rates 50, 100, 150 and 200/Yr. (from COMET/OCM)

Figures 7, 8 and 9 illustrate the results of the PrOpHET analysis, estimating O&M hours per pound of subsystem dry mass. Although lighter vehicles would tend to have lower requirements in general by this approach, this was offset by comparing each concept by subsystem independently to the baseline and adjusting the hour/lb. factor up or down accordingly. The rankings in Fig. 7 are similar to COMET /OCM, although developed by a very different model. The four concepts lowest in O&M hours (preferable) are the same. Waverider competes better, slipping below Kaiser Marquardt (KM). Adjusting by concept mass fraction rearranges the mix somewhat. Sorting by hours per pound of payload drives Hyperion out (discussed elsewhere) and gives Waverider and KM the edge over the ACRE's.

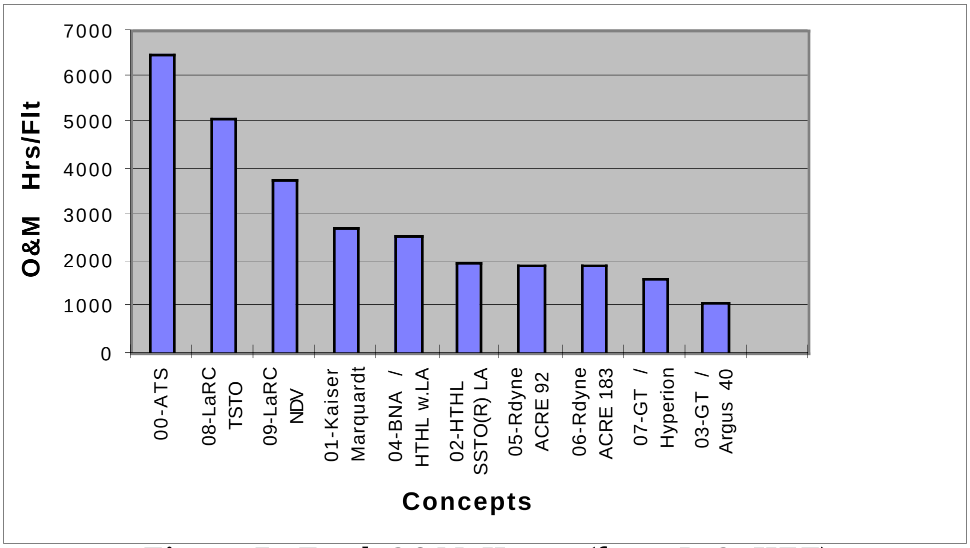


Figure 7: Total O&M Hours (from PrOpHET)

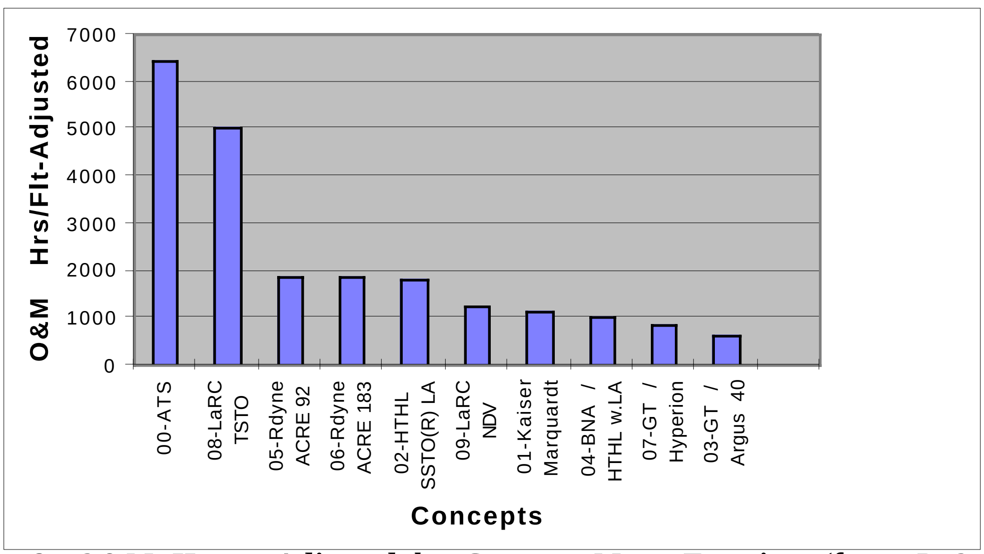


Figure 8: O&M Hours Adjusted by Concept Mass Fraction (from PrOpHET)

Figure 10 shows the level of maintenance burden required for technologies used on the HRST concepts. When HRST support goals are used as constraints, the model results show the need for orders of magnitude improvements in the reliability of those systems which have proven to be maintenance drivers on Shuttle, and reductions in the time and manpower needed for repairs for all of the concepts. The values in column 1 illustrate the effect on maintenance burden of using technologies on the HRST concepts whose characteristics are like those of the comparable Shuttle technology. The maintenance drivers remain the TPS, structures and the propulsion systems. Columns 2 and 3 respectively represent the reductions in maintenance burdens that can be achieved by new technologies to reduce the number of maintenance actions required, and the time required to repair systems. Column 4 illustrates the burden when both of these effects are characteristics of new technologies. Both were necessary to meet the HRST support goals.

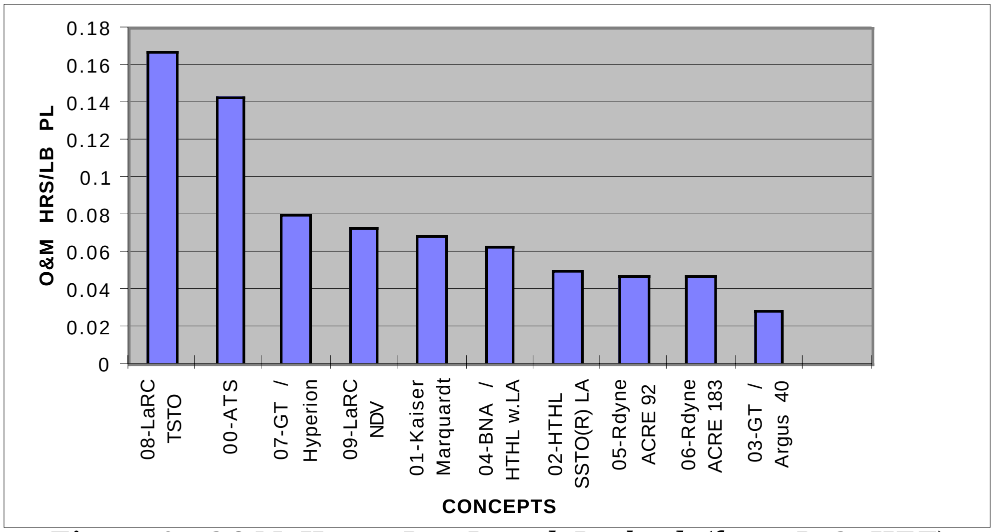


Figure 9: O&M Hours Per Pound Payload (from PrOpHET)

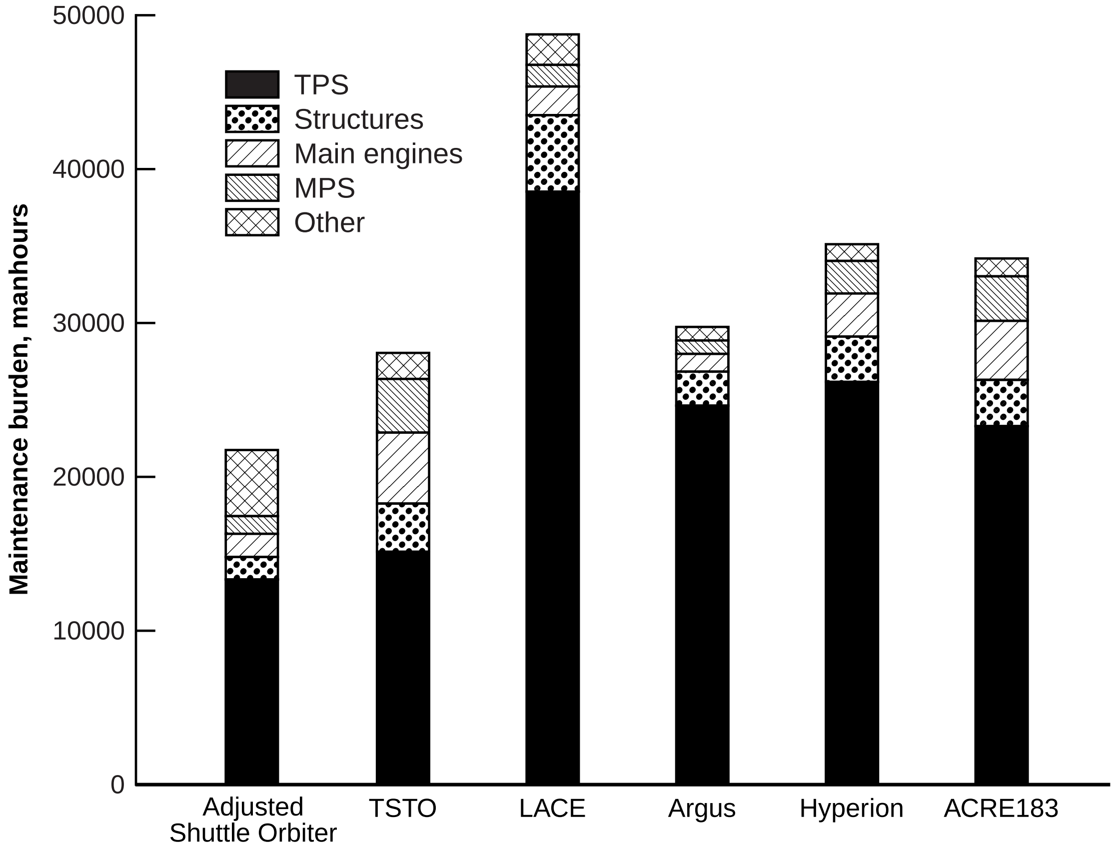


Figure 10: Maintenance Burden (Workhours) by Subsystem (from RMAT)

Although these reductions in Shuttle support requirements may appear large, they may not be that difficult to achieve. Current Shuttle support represents support for systems that lack maturity, at least relative to aircraft systems. Therefore, the maintenance required, both in frequency and in repair time reflect the relative lack of experience in dealing with these technologies in this environment. As this prudent approach matures, experience will contribute to these required reductions by better being able to judge when maintenance is required and by increased confidence in the repair process. New technologies such as the use of vehicle health monitoring will help to reduce the time required to detect and isolate problems before repair. In addition, all new technologies will have an extensive test program to assure that these R&M characteristics are achievable, before inclusions on the concept.

The differences in results illustrated here are due only to the size, number of systems, and system requirements. Differences in specific technology choices are not reflected in these results, however, the R&M characteristics defined apply to all the HRST concepts. All will require system technologies that have been developed, tested and proven to have support requirements orders of magnitude less than that currently in use. This will both reduce the personnel involved and shorten the time required for maintenance to better utilize the vehicles in productive service

Of interest here is not only how the concepts ranked relative to one another, but also which subsystems were the drivers - TPS and main engines, which result was incorporated into the OCM/COMET and PrOpHET models. Here LACE fares poorly by comparison due to the extensive cooling requirements, through both active and passive subsystems that require high maintenance. In this approach, TSTO competed well with the other concepts, due at least in part to the relative simplicity of both the first stage and the orbiter. RMAT did not consider processing requirements outside of the VPF, such as the integration of the stages. Argus and ACRE 183 were very close, with ACRE 183 losing the advantage due to main engine and MPS maintenance burdens (six engines on the first stage and three on the second.)

RECOMMENDATIONS

The HRST Integration Task Force, Operations, believes that the following recommendations will enable continued advancement toward the goals of the HRST study, routine and highly affordable access to space.

RECOMMENDATION 1. Architectural, global optimization of designs is required to achieve HRST goals. Optimization at component or sub-system levels must be only one part of a broader improvement strategy focused on affordable architectures. Large-scale optimizations that rethink major design decisions must be improved upon across the board to achieve HRST goals.

The Ops Team developed a set of "Architectural Guidelines" which expand on the need to optimize designs and technology around broad, global features. The Guidelines are derived from the work of the Space Propulsion Synergy Team (SPST), a multi-industry-NASA-academia and government-entrepreneur group. This work by the SPST was in support of the HRST project. These Guidelines are outlined ahead in the section "Architectural Guidelines." Further, the Team developed more specific recommendations, or "Rules of Thumb", for applying system margin (See Guideline 1.2,"Fielded Margin") to vehicle design for enhancing operability. This particular objective, margin - the ability to field a system that is not operating near the edge of it's design limit, can be one enabling factor for the incorporation of multiple other features which make a space transportation system more affordable to acquire and to operate. The improvement, or not, in all of these major areas outlined below is crucial to achieving a total system, flight and ground, capable of one day meeting HRST costs goals. These specific recommendations are listed ahead in the section "Rules of Thumb."

RECOMMENDATION 2. Demonstrators are required that prove the proper flight regime and the more complex systems that may associate with rocket based combined cycle (RBCC) concepts.

Anchoring the benefits of airbreather propulsion through demonstration will allow quantified understanding of the proximity to achieving the HRST operational objectives. Basic R&D, component, system and integrated testing focused on advanced propulsion development is required to sidestep inherent all rocket limitations.

RECOMMENDATION 3. Margin Benefits: Future concept definition for airbreather space transportation systems must provide links to margin benefits.

Realistic estimates are required of resulting margins from airbreather approaches correctly accounting for additional systems unique to airbreathers such as active cooling, active geometries and associated actuation mechanisms, fans, etc. The effect of this margin on other systems such as TPS, structures, power and subsystems, and flight and ground must be further understood (Ref. Recommendation 2).

RECOMMENDATION 4. Two major systems areas require technology development: propulsion and thermal protection (highly linked for airbreather concepts.)

For commonality with multiple avenues, and with enabling benefit, they become priorities:

- **Ejector ramjet (ERJ) R&D and demonstration.**
- **Ejector scramjet (ESJ) R&D and demonstration, build on previous.**
- **Thermal protection systems (TPS) - passive, zero waterproof, robust against damage.**
- **Thin leading edge passive TPS.**
- **Thermal protection systems (TPS) - active, robust, low maintenance (as fallback).**

Active and Passive Cooling: Active cooling should compete in this priority in so far as it is requisite; passive cooling developments should focus on the potential elimination of any active cooling requirement at leading edges, inlets and at other structures as required. Active cooling should be considered a backup or fallback technology. Key technologies that enable low cost operations are as follows:

- **Reusable propellant tankage and feeds (cryogenic service) - composites.**
- **Integral, conformal propellant tankage (for all propellants).**
- **Robust, maintenance-free thermal protection systems.**
- **Electric actuation, high horsepower - eliminate hydraulics, applies to propulsion geometry and aerosurfaces.**
- **Power systems, simplified, non-toxic, low and high horsepower - eliminate hypergols, eliminate multiple different types of power systems to service and maintain.**
- **Common propellant systems (propellant grade fuel cells, orbital maneuvering systems (OMS) and reaction control systems (RCS) using propellants common with main propulsion).**
- **Vehicle and ground health management systems (VHM/HM).**

RECOMMENDATION 5. Operations Cost Modeling: The conceptual phase of any study activity is limited by broad characterization and less specific information. By it’s nature the intent is to avoid allocating into a program before preliminary study has been undertaken. Cost modeling with an ability to work on limited types of information is required.

Models based on more specific information have also been noted as an area for agency improvement since even operational systems such as Shuttle do not adequately account for and explain costs of operations with any traceability that allows decision making focused on improvement. It should be re-iterated here that a major factor, if not the major factor, in cost modeling for space transportation systems is the launch rate capability of the concept, the effect of which was discussed in "Discussions and Conclusions" (above).

RECOMMENDATION 6. Operations Cost Measure Of Merit: A measure, “useful payload per year to LEO per vehicle” is proposed as an equalizer that allows the benefit of systems with less payload but more response (flight rate at a given resource expenditure or cost) to be measured against systems with less response and higher payload.

The ideal is more payload as well as higher flight rate. Less payload per flight should not be assumed undesirable except as applies to particular markets.

RECOMMENDATION 7. Building an Earth-to-Orbit (ETO) Technology Roadmap (Ground & Flight Demonstrators - “Pathfinders” & “Trailblazers”): The next step beyond HRST efforts should be to build a technology roadmap that defines a phasing plan for ground and flight demonstrations.

However, the concepts, as provided, are not yet to a level of maturity for clearly determining which will achieve HRST goals. That being the case, a roadmap that leads to architectures achieving operating costs below $1,000 per pound is likewise premature. It is recommended that an iteration process be initiated on the provided concepts. The iteration process should be guided through the use of the suggested design "rules of thumb" (see below.) Once the concepts have reached maturity, or the HRST goals are assessed as having been met, then the nation will be ready to construct an ETO roadmap that leads to a portfolio of promising architectural concepts that are capable of achieving $100-$200 per pound cost. In the context of these promising architectures, the technology requirements could then be formulated.

RECOMMENDATION 8. Concept Programmatic Information Needs to be Better Identified and Clearly Separated Between R&T and Commercial Acquisition Commitment Phases.

As the iterative process unfolds, better definition of cost and schedule should be made available. Particularly needed, however, is clear discrimination between which are incurred during the research and technology phase, and which are incurred during the commercial acquisition phase. This clear discrimination is required to build an effective research and technology program that reduces high cost and risk investments associated with commercial acquisition.

RECOMMENDATION 9. Final Recommendation to HRST Study Team: Avoid Presenting Premature Architectural Selection.

Premature architectural concept selection at this point will lead to a programmatic commitment that would fall well short of the Civil Space Transportation Study goal of engendering space market growth.

ARCHITECTURAL GUIDELINES

As discussed in Recommendation 1 (prior), HRST goals will not be realized without architectural, global optimization of designs. A broader improvement strategy focused on affordable architectures must be implemented. The following Guidelines, applicable to space transportation system design at the architectural level, are derived from the work of the SPST and are listed in order of effectiveness in reducing the operations burden:

1.1 Guideline: Fluid selection for ease of operability & supportability.

a. Avoid use of fluids that are toxic and require ground-handling controls for personnel protection or environmental control reasons.

b. Avoid use of fluids that are flammable, other than for propellants purposes, to avoid need for additional fire protection at various ground stations.

Benefits: Increases safety, operability and required support, which results in less manpower, faster vehicle turnaround and lower recurring cost.

1.2 Guideline: Fielded margin (that which remains upon completion of the space transportation system acquisition) increased for mission flexibility and improved operational effectiveness.

a. Provide fielded margin in all vehicle system disciplines to allow customer and space transportation system mission flexibility.

b. Use some of this fielded margin to increase the operational effectiveness, i.e., trade weight for concept attributes that improve operational characteristics like dependability (use of COTS) or better functional integration to delete large ground infrastructure support at launch site and manufacturing.

Benefits: Increased mission flexibility of the space transportation system to better meet the customer's needs. Allows system trades on the concept design that increase potential of meeting the recurring cost objectives and engendering space market growth.

1.3 Guideline: Increase the vehicle and ground systems health management capability to allow increased space transportation system responsiveness to customer needs and labor reductions to provide reduced recurring cost.

a. Provide BIT/BITE for all vehicle and ground systems (electrical, mechanical & structural) components. Embed fully automated routines that reduce ground turnaround time, labor and hands-on activities required to operate, verify component integrity, as well as perform troubleshooting and retest following corrective action/maintenance.

b. Provide built-in sensing network systems to allow automated inspections of all structural, TPS, and mechanical systems (which traditionally are inspected manually).

Benefits: Systems that are fully automated (flight and ground) will decrease vehicle turnaround, increase vehicle availability, reduce hands-on activities and collateral damage, reduce labor required and achieve large reductions in recurring cost. This avoids major out-of-service inspection operations.

1.4 Guideline: Design for passive environmental control and avoid hazardous confined spaces—or confined spaces that require personnel entry (both planned and unplanned).

a. Design system layout so that component change-out can be accomplished without entry into confined spaces.

b. Provide airframe design to allow both ground and flight environments to be controlled through a passive design means. This avoids closed, hazardous confined spaces that must be maintained safe using active systems (GN2/air purge and hazardous gas detection systems).

Benefit: Delete need for large amounts of ground infrastructure to purge confined spaces. Infrastructure eliminated includes: purge air systems for personnel needs, purge systems of the same area with GN2 for flammable/detonable gases, hazardous gas detection systems, and personnel access kits. Added operational benefit in terms of responsiveness includes elimination of personnel entry & control for safety. For example, mid-body and aft closed compartments can cause collateral damage and unplanned work if system hardware is not located on walls with external access. Elimination of closed/confined spaces, therefore, reduces manpower required, less ground turnaround time (greater flight rate capability per vehicle), reduced logistics tail for replacement parts and supplies, less ground infrastructure to operate and maintain, safer environment for personnel operations- all resulting in greatly reduced operations cost. Also reduces acquisition cost of both flight and ground hardware and associated facilities.

1.5 Guideline: Provide an ideal overall propulsion packaging architecture that results in minimum hardware support requirements and flight-to-ground interfaces while also yielding the most reliable/dependable space transportation system.

a. Provide common integrated single vehicle propulsion system that performs the main ascent propulsion function (MPS), the on-orbit/de-orbit propulsion function (OMS), and the non-and rarefied atmospheric reaction control system (RCS) function. For operational improvement, these functions must use only one set of propellant tanks, with only one set of ground support servicing systems. For example, the OMS can be to supplied from the main propulsion feed manifold sized for this function, and the RCS could be fed from the ullage gases supplied using an automated compressor/accumulator gas system.

b. Provide for integration of electrical power generation (fuel cells/turbo-alternators) and any active thermal management of on-board systems with the integrated propulsion single set system. Ullage gases from the main propellant tank set using an automated compressor accumulator gas feed system should supply these functions.

c. Provide propulsion sizing to accommodate all requirements with minimum number of engines (two engines ideal but no more than four)

Benefit: Deletion of functionally redundant systems, i.e., separate propellant tanks, pressurization systems, pneumatic controls, flight-to-ground umbilicals, avionics support for tanks fill & drain values, and very large ground support infrastructure at the launch and manufacturing sites. Large reduction in part counts and support logistics. Also allows the use of non-usable residual gases from traditional concept. Results in large reduction in manpower, replacement hardware cost, reduction in sustaining engineering and manufacturing support. Net benefit is faster turnaround (more responsive and available transportation system) more reliable/dependable system (less systems and backup systems) and large reduction in recurring cost. Also should result in less acquisition cost.

1.6 Guideline: Provide a space transportation system with minimum unique stages (flight and ground) and design-to interfaces.

a. Provide a very integrated single stage concept with only one set of

propellant servicing interfaces and only one power interface to ground.
b. Provide propulsion system with minimum interfaces to vehicle, i.e., provide integrated propulsion system to allow minimum functional requirements like main propellant pumps placement with main tank to eliminate chilldown and conditioning requirements to operate the main engines. In addition, placement of the main LOX tank in aft end to eliminate complex and time-consuming servicing requirements like chilldown, anti-geysering and pogo systems for flight.
c. Provide simplified payload to vehicle interface with minimum support and functional requirements, i.e., only structural attachments. Use the same attachments for every flight and payload. The payload enclosure should provide any unique support, i.e., contamination control, electrical power, data management, fluid services and purge (if needed) or even life support if personnel are included.

Benefit: This will reduce the number of ground processing/checkout stations, assembly and integration stations, and very large amount of unique ground support equipment. It will also greatly reduce the number of manufacturing and stage assembly facilities. Will result in a very large reduction in logistics of consumables, replacement parts, and labor headcount. Will achieve much shorter ground turnaround time (higher single vehicle flight rate capability) resulting in a large reduction in acquisition and recurring cost.

1.7 Guideline: Provide a space transportation system that is simple, i.e., very small number of manufacturing, test, and operations facilities, with only a minimum number of different/complex parts, often resulting in active ground servicing requirements.
a. Provide a simple highly integrated/automated single stage vehicle.
b. Provide a simple highly integrated/automated single stage vehicle without launch assist or active ground systems to accommodate launch acoustic, cooling, and ignition overpressure environments.

Benefit: A simple, single-stage space transportation system will achieve large reductions in manufacturing, special test and launch facilities. In addition, the resulting unique ground support equipment associated with multi-stage concepts are eliminated, providing shorter ground turnaround time, less labor headcount, more available and responsive system to payload customer needs, and a large reduction in acquisition and recurring cost.

1.8 Guideline: Provide a simple vehicle with a minimum number of different fluids or gases with unique vehicle-to-ground interfaces.
a. Provide a vehicle system that only requires a single set of fluids to accommodate all functions for the space transportation system.
b. Provide a vehicle system that only requires one single gas on-board that accommodates all functions required.
c. Provide a vehicle that does not require on-board purges and no purges to maintain safe vehicle on the ground during servicing for flight.

Benefit: Ground servicing will require only a few ground servicing systems resulting in very large reduction in ground servicing systems at several facility stations. This in turn achieves a large reduction in labor headcount, acquisition and recurring cost. Large reductions in logistics of replacement parts, consumables, sampling, filtering and conditioning systems, labor and recurring cost and cycle time.

1.9 Guideline: Provide a simple vehicle with a minimum number of ground electrical power servicing requirements.

a. Provide a flight vehicle system that provides its own power management on-board requiring only one vehicle-to-ground interface at each ground facility station.

Benefit: Greatly reduced flight-to-ground umbilicals, ground servicing systems at each station, large reduction of parts, reduced logistics, reduction in labor headcount, more responsive transportation system, and large reduction in acquisition and recurring costs.

1.10 Guideline: The space transportation system only uses highly reliable/dependable parts, components, and systems-and are ground and flight demonstrated/certified to be such during the development phase prior to system acquisition. Use of demonstrated highly reliable/dependable systems results in a fielded design that requires very infrequent unplanned maintenance.

a. Select hardware that is commercial-off-the-shelf (COTS) and that has a very high demonstrated meantime between failure (even if the hardware isn't the lightest weight-the resulting increase in flight rate will more than make up the weight difference of one launch).

b. The use of laser igniter technology hydrostatic turbopump will provide reduced stresses on rocket during start transition (no longer constrained to flammability limits) by decreasing the ramp-up rate. The new bearings will also provide greater MTBF.

c. Operate the rocket engines at reduced maximum designed power level.

Benefit: A space transportation system that is very responsive and available in meeting customer needs at lowest recurring cost. Specifically, it results in a low level of logistics (including the rocket engine element) for replacement parts and minimum labor headcount, as well as a reduction in collateral damage from component replacement and troubleshooting on the vehicle.

1.11 Guideline: Provide a space transportation system with only a few connections required to integrate the major functions and their components. (Avoid design-in potential leak connections, tubes, hoses, ducts, etc., for fluid and gas systems; and electrical mating connections, wiring, switch-gear, etc. for electrical power, data, command & control, communications systems).

a. Provide designs that do not require leak testing verification for fluids and gases for both static and dynamic applications, i.e., nearly all-welded systems.

b. Provide designs for electrical power and data transmission without the use of thousands of cable connections providing potential failure resulting excessive, time-consuming troubleshooting, repair and restoration to flight certified condition.

Benefit: Much safer, more reliable, and simple system to operate. Also far less unplanned work, operations stoppage (cycle time, launch holds and scrubs, etc.) Results in lower recurring cost as well as faster acquisition schedules to bring the system through certification.

RULES OF THUMB

Guideline 1.2 (prior) is to have a design that has fielded margin. The term margin is not used here in the traditional programmatic sense. Programmatic margin is simply a way of dealing with uncertainty and is by definition used up in design and development simply to achieve function and performance. The margin referred to here is left over and either (1) fielded in the system as in more robustness or (2) used to selectively alter and improve the basic design and make the system more operationally affordable. Assume that a launch vehicle could be so developed that when fielded, it could deliver the required payload to the destination without operating at maximum performance levels, If so, weight could be added to the vehicle without affecting it's delivery capability. How could this weight be best used in or allocated to the vehicle subsystems to make them more robust, reliable, dependable and reduce operations and maintenance burdens with the intent of reducing operations cost?

In short, if we assume that a vehicle design will result in margin when fielded, how could we apply that margin to the design to increase operability and enable low ($100/lb of payload) recurring costs?

In response, the Ops Team developed the following list of ways in which "margin" (weight) should be used to increase vehicle "operability". Specific examples follow of areas where margin as considered here can be used to result in a more affordable operation "by design". Not all these should be considered de facto increases in weight or as being uniquely achievable through margin. Rather, the existence of more margin can serve as one important enabling factor in bringing about these features in a fielded system.

Operations and Overall Affordability:

Propulsion and Engines:

- De-rate the engine operation to reduce stress. Design and certify to one level, operate at less (example: engine operation at 90% of design/certification thrust). This should extend life through a direct increase in MTBF for many major components. A study by MSFC/Rocketdyne, "Rocket Engine Life Analysis", August, 1996, indicates a significant increase in engine life expectancy, from 10's to 100's of flights between overhauls, when operating engines at 90% rated capacity.

- Reduce start/stop transients for engines through either technologies (laser ignitors) or approach (increase propellant capacity and slow the startup). Any decrease in engine ramp rate correlates to reduced thermal shock loading on materials and increased life.

- Eliminate hypergols. Use fluids already common to the main propulsion system such as LOX or LH2. Volume and hence weight has previously limited use of LH2 in favor of toxic fluids.

- Make propellant tanks more robust (through increased weight *or* stronger materials with higher design factors of safety or both). This should simplify checkout and loading procedures by eliminating complexities associated with fragile tankage.

- Make umbilical interfaces more robust on the vehicle to enable automated connection and disconnection of umbilicals with simple checkouts. Fragile, flight-weight structures on the vehicle side severely constrain (or eliminate) options for automation of umbilical connections at multiple interfaces Automation would move connection time towards minutes rather than days.

- Place LOX tanks aft. This simplifies facilities for loading as well as loading procedures by eliminating failure modes and additional complex systems. If using engine gimballing, this may mean increased control authority. This in turn may involve engines placed farther apart.

- Swing arms should be eliminated or vent lines placed fully on-board. The simplification of interfaces could be improved by eliminating vent arms for cryogenic boil-off. Overboard venting may involve more robust thermal protection systems and structure capable of resisting ice formation and possible impact. Fully on-board vent lines, as another option, can be routed down and integrated with ground umbilicals to reduce overall complexity.

- Add propellant capacity to allow extended loiter [airbreathers] and eliminate non-return-to-launch-site abort modes. This eliminates costly stand-by-contingency infrastructure.

Vehicle and Structure:

- Increase robustness to eliminate regular intrusive checkout and inspection. This should be targeted on an increased tolerance to corrosion and stress.

- Thermal protection systems should increase weight if required to make more robust. This enables use of a higher impact material that is damage resistant.

- Thermal protection systems should be purge-less for zero interface support requirements. This may mean an increase in foam thickness. The elimination of confined spaces and creation of a purge-less condition is a target.

- Increase landing gear robustness. Size correctly for true “walk-around check only” reusability at expected loads, speeds and operating conditions.

- Closed compartments should be eliminated. As stated several times in the body of the report, the negative impact on operations in terms of time and resources that result from confined spaces in the vehicle cannot be overstated.

Health Monitoring and Control:

- Integrated Vehicle Health Management should increase the number of sensors focused on maintainability (ease and speed of troubleshooting, fault detection and isolation, and checkout). This should permeate fluid, electrical, and structural systems - not just black boxes.

- Electrical onboard power should provide simple, single connection and on-board conversion for simplified interface to ground during processing (airplane like). On-board ability to power specific systems as required should be built in.

Supportability:

- Increase accessibility by means of aircraft-like access panels. This includes motorized, hinged, latched, pull out access trays and operator access via push button. Maintainability, post troubleshooting, is increased, reducing mean time to repair.

- Design for self-ferry. Simplified infrastructure via the on-board accommodation of most, if not all functions required for take-off is a target.

- Use commercial-off the shelf (COTS) hardware with little or no modifications to get flight weight, i.e., aircraft weight.

Payload:

- Create more independence for the payload to simplify integration. A containerized system with a very simple, robust loading operation (sea-land type, self-sustaining containers) is a target.

APPENDIX A - Highly Reusable Space Transportation, an Advanced Concepts Study, Project Guidelines - Operations

Markets and Payloads

Concepts and/or architectures must accommodate (launch and return) all current and currently planned future civilian government, commercial, and national security payloads.

Concepts and/or architectures must accommodate a wide range of different types of future payloads, including private citizens as passengers, government/military passengers, individual or multiple satellites and other spacecraft (including any required propellants or upper stages for transfer of satellites or systems to other orbits), bulk materials (e.g., water or propellants in tanks), and nominally 'hazardous' materials (appropriately packaged).

Orbits

For reference purposes, concepts and/or architectures must be able, as a minimum, to provide transportation of payloads to a 100 nautical miles circular orbit at 28.5 degrees inclination.

Note that this orbit will be defined as "low Earth orbit" (LEO) for purposes of this guidelines document; other orbits will be indicated as appropriate.

Reliability and Safety

Reliability objectives have been developed that are consistent with economic objectives of HRST (i.e., must be 99.9% for launch costs to be less than $100-$200 per pound) as well as with the goal of moving toward airplane-like capabilities, including the requirement that these systems be capable of highly reliable overflight of populated areas during launch. In particular:

Reliability of flight vehicles vis-à-vis catastrophic loss should be 99.99% (i.e., the probability of a system failure resulting in vehicle loss should be less than 0.01%). Safe return and recovery of passengers and/or precious cargo should have a higher probability by a factor of five-to-ten (i.e., up to 99.999% probable).

Flight vehicles should be essentially 'fail safe' over land i.e., with 99.999% probability of no ground fatalities or extensive property damage per launch.

Concept Payload Accommodations

New HRST vehicle concepts must accommodate individual payloads that range from 20,000-to-40,000 lb. (i.e., approximately 10-to-20 MT) in mass.

Vehicle concepts must accommodate individual payloads that are no less than approximately 6,000 ft^3 (200 m^3) in volume in a payload bay not less than 15 ft (4.5m) in diameter. Note that with a diameter of 15 ft, this is consistent with a payload length of approximately 35 ft.

HRST technologies and/or systems should also accommodate the launch of smaller payloads, in the range of 1,000-3,000 pounds, to LEO with costs of less than $1000 per pound.

Operations

Individual ETO reusable systems referred to as 'flight vehicles' should be able to 'launch' more than 50 times per year (i.e., approximately once per week, or more).

Flight vehicles should be able to launch payloads that are traveling to 'all' orbits ranging from equatorial to polar and ranging from 100 nautical miles to geosynchronous altitudes or beyond. Meeting this functional requirement may involve the use of upper stages and/or thrust augmentation of a flight vehicle and would entail appropriately varying payload performance.

HRST concepts must be capable of operating completely self-sufficiently in LEO for a minimum of 48 hours (with the exception of minimal ground or other external monitoring of HRST operations).

Ground-based infrastructures at each active launch site, such as ETO vehicle processing facilities, must be capable of processing more than 200 vehicle-visits per year (for example, approximately four per week, or more) (This might entail four vehicles, each operating once per week, or fewer vehicles, each operating more than once per week.)

For the level of flight operations cited above, total ground operations personnel should be less than 250 'direct charge' individuals.

Flight vehicles should be able to launch and land in near all-weather flight operations conditions (like aircraft), with rapid turn-around of individual vehicles for re-launch.

Life Cycle Costs

Individual operational flight vehicles should cost less than $1B per vehicle, including manufactured cost, but not including technology, system development or infrastructure costs. (Reference: a Boeing 747 passenger jet is priced at approximately $150M per aircraft, where total production runs are in quantities of over 1000 aircraft.)

Total recurring operations costs per flight vehicle, with launch rates of once per week for the vehicle, should be less than $200M per year (i.e., approximately $4M per flight operation).

The cost contribution due to flight vehicle hardware costs should be less than $50 per pound of payload per flight (including costs to replace the vehicle at the end of system life, the expected cost of vehicle failures, and the cost of hardware replacement items for vehicle maintenance e.g., spare parts). For the stated payload range, this amounts to $500K-to 1M per flight operation.

System Reliability, Maintainability and Life

In general, operational flight vehicles should have an effective lifetime greater than 2000 flights.

Selected major vehicle systems (in particular, engine sets) should have either: an effective lifetime between scheduled major removal and maintenance operations greater than 22 flights if the cost of that system is greater than 10-20% of the value of the entire flight vehicle, or an effective lifetime between scheduled major removal and maintenance operations greater than 5 flights if costs of the particular system are more than 1-2% of the value of the vehicle, or less.

Operational flight vehicle performance margins should be significantly greater than those projected from the HRST Reference Vehicle, particularly for high-operability scenarios and cost-critical subsystems e.g., engines. The level of increase may vary from system to system, but the net result should be significant increases in lifetime, operability, etc., and reduction in repairs, spares, failures, etc.

Generally, and as appropriately modified, operational flight vehicles should be capable of incorporating vehicle performance-enhancing systems that permit higher delta velocity and or increased payload mass missions to be performed, including initial launch assist systems (such as electromagnetic catapults) or in-flight thrust augmentation (such as strap-on rocket assist systems) and other load-transfer design features. For example, if a particular HRST system concept is capable of launching 35,000 pounds to LEO, it should also be capable with thrust augmentation of launching 35,000 pounds to the planned International Space Station Alpha orbit (220 nautical miles, 51.6 degrees inclination).

Operational flight vehicle systems and/or their related technologies must support NASA science and/or exploration missions with "reasonable" adjustments (e.g., by being serviceable over a broad range of payloads).

There should be clear dual-use opportunities at the system, subsystem, component and/or constituent technology levels. These technology-transfer opportunities may be applicable to national security, private sector commercialization, or other sectors; the broader the applicability, the better.

National Policy

HRST results and recommendations must be consistent with the General Agreement on Tariffs and Trade (GATT) and related treaties and/or international agreements.

HRST results and recommendations should be consistent with the US National Space Transportation Policy (1994).

HRST results and recommendations should further national policies and objectives relating to dual-use of technology, and technology transfer and commercialization.

Past and Ongoing Space Launch Technology Programs

The HRST study and resultant system concepts will use as a baseline the NASA Access to Space study's Option 3, All-Rocket, single-stage-to-orbit (SSTO) case as its Reference System (with any appropriate updating, scaling or other adjustments to allow more appropriate comparisons to advanced systems concepts).

HRST Study-Defined Technology Programs

Technologies needed for HRST system concepts must be capable of being brought to a prototype systems level of technology readiness level with "reasonable" technology investment levels by no later than 2005-2015 for mid-term concepts. Technologies needed for very advanced concepts may not be able to achieve technology readiness for development until post-2015. Note that this is not a restraint on availability for either class.

Total required HRST-specific government civilian space program (e.g., NASA) technology research and development investments (including R&D facilities, but not including large scale flight demonstration vehicles) should not be greater than $200M-$300M per year.

The specific level of HRST-related government technology investment may vary upward from the range cited above depending on the degree to which these investments and capabilities gains are 'dual-use' with potential to be augmented via multi-Agency (US) and/or international sponsorship and/or collaboration.

Procurement of operational flight vehicle systems and close-in supporting infrastructure (e.g., vehicle ground servicing equipment) must be 100% privately financed.

Engineering development (through theoretical first unit, "TFU", delivery) of operational vehicle systems must be no less than 50% privately-financed.

Technology development and demonstrations related to a specific HRST system must be no less than 25% privately financed.

General technology development and validation relating to very low cost space transportation through HRST concepts may be down to 0% privately financed.

Broadly available macro elements of infrastructure (e.g., launch sites and general flight traffic support systems) may be down to 0% privately financed.

“Special Technical Area(s) of Interest” pertinent to operations are defined in the “Guidelines”:

Operations

To meet market objectives, HRV/HRST systems must achieve unprecedentedly low levels of personnel and support equipment involved directly or indirectly in operations. For initial flight rates, achieving market goals will require single-item manufacturing at large-scale manufacturing-like costs. Diverse technologies and concepts (such as those described above) will require evaluation against common criteria/objectives and against one another. Dynamic simulation of operations (flight cycle-to-life cycle) will be essential.

Manufacturing

Although initial HRV’s may be relatively expensive, advanced manufacturing approaches for HRST vehicles must be defined in such a way so as to enable open-ended low-cost manufacturing of spares/parts for operational vehicles as well as of new vehicles as markets develop and fleet sizes expand. Developing strategic approaches to low initial and continuing costs in manufacturing is needed.

Thrust Augmentation and Upper Stages

Addressing the total market from a payload destination standpoint may require the use of thrust augmentation (e.g., strap-on solid rocket motors) and/or upper stage transfer stages to allow higher than low Earth orbit (LEO) delta-velocities. Such provisions will also satisfy the launch of a particular payload to a higher or different orbit than the reference.

Primary issues here will revolve around the impact on total life cycle costs of allowing for this possibility and the specific cost and performance of various approaches to thrust augmentation. This conceptual approach will be traded against overall HRV scale, capability and system costs in other study options cited above. Each of these will be a minor study emphasis.

Planned Balance of Risk and Payoff in HRST Projects

It is anticipated that the portfolio of projects conducted during HRST Phase 2 will represent a balance between nearer-term (e.g., next 10-20 years) and farther-term (beyond 20 years) concepts, with appropriate increases in the levels of payoff and risk for the farther term opportunities.

APPENDIX B: Description Of Concepts

The following outlines the particular HRST concepts considered in this assessment.

1. Vertical Take-off, Vertical Landing (VTVL) Supercharged Ejector Scramjet (SESJ) Single-Stage-to-Orbit (SSTO).
    - Kaiser Marquardt (with Georgia Tech.)

Payload is 40,000 to 100 nmi circ. at 28.5 degrees with 1.04 Mlb GLOW and 184.6 klb dry weight. Airbreathing to rocket mode transition is at Mach 12 nominal per reference 4.

This concept is a VTVL SESJ employing an engine with a fan/gas generator. The concept uses 12 engines with 2 engine out capability. The reference information for this is (1) "Rocket Based Combined Cycle Powered Spaceliner Concept" by William Escher, NASA Headquarters and Paul A. Czysz, Saint Louis University, Parks College, (2) "Highly Reusable Space Transportation Architectural Assessment Form" provided by William Escher, Kaiser Marquardt, (3) notes provided by William Escher in response to the prior form / questionnaire and (4) Information package provided by request of the HRST Integration Task Force, Operations.

2. Horizontal Take-off, Horizontal Landing (HTHL) Supercharged Ejector Ramjet (SERJ) Non-waverider Type Single-Stage with Launch Assist.
    - Georgia Tech Aerospace Engineering, "Argus"

Payload is 20,000 lbm. to LEO (easterly) per reference 1, with 596.4 klb GLOW and 76.4 klb dry weight. Airbreathing in ramjet mode is to Mach 6 then transition to rocket.

This concept is a HTHL single stage with launch assist. The concept has 2 SERJ engines of 209 klb thrust (sea level static). Ramjet is used to Mach 6 then rocket mode. Engine similarity in use of the fan (but not scram capable) to the Kaiser Marquardt concept. Concept is 171 feet in length nose to tail. The reference information for this is (1) "Argus" briefing by Dr. John Olds, Peter Bellini, David McCormick, Patrick McGinnis and Mike Lee of Georgia Tech Aerospace Engineering, Aerospace Systems Design Laboratory and (2) Information package provided by request of the HRST Integration Task Force, Operations.

[Note: 40,000 lbm. version also assessed.]

3. Horizontal Take-off, Horizontal Landing (HTHL) Rocket Based Combined Cycle (RBCC) Waverider Type Single-Stage with Launch Assist.
    - Boeing North American (BNA)

Payload is 40,000 lbm. to 100 nmi, 28.5 degrees with 1.04 Mlb TOGW and 212.1 klb dry weight.

This concept is a HTHL single stage waverider hypersonic L/D=5 configuration with launch assist. The concept is similar in class to the “Argus” concept. Differences are principally the body configuration being waverider derived and the use of more engines at lower thrust (8 engines at 72,130 lb. thrust each at sea level) plus a higher payload and system weights. Internal details are partially indeterminate. For this review they are assumed: conformal but not integral as with Argus, with TPS purges and partial external tank aeroshell versus no aeroshell on Argus, and with Waverider driven multiple propellant tanks due to it’s form, versus single tanks in Argus. Also, OMS is integral to main propulsion, unlike Argus with separate OMS/RCS. The reference information for this concept is (1) Briefings to the HRST project and (2) Information package provided by request of the HRST Integration Task Force, Operations.

[Note: Multiple other weight configurations also assessed.]

4. Rocket, Baseline Comparative System Update, Using Advanced Chemical Rocket Engine (T/W engine = 92).
    - Boeing North American (BNA) - Rocketdyne

Payload is 40,000 lbm. to LEO with 1.98 Mlb GLOW and 182 klb dry weight. [Note: 20,000 lbm. case also sized.]

This concept is an update on the Access to Space study Option 3 bipropellant all rocket single stage to orbit. The delta is the use of a new engine one generation beyond those proposed for the Reusable Launch Vehicle (RLV) program. The basic approach is to (a) design out life limiting lessons learned from the STS/SSME program, (b) test to drive out failures and define operating limits, (c) operate in a less severe environment, (d) design in power margin (such as 10%, and do not use this margin for normal operations), (e) move to higher power margin cycles (full flow staged combustion, Ox-rich, versus fuel rich staged combustion to lower turbine and preburner temperatures and allow uncooled powerhead) and (f) use new technology to extend engine life. This last approach includes turbopumps with fewer parts (SLIC based), jet pumps versus low pressure turbopumps, laser ignitors to decouple start and shutdown from flammability limits, combustion chambers with lower wall temperatures, hydrostatic bearings for turbomachinery and new materials. The reference information for this concept is (1) Briefings to the HRST project on “Advanced Rocket Engine” and (2) report NAS8-39210.

4. Rocket, Baseline Comparative System Update, using Advanced Chemical Rocket Engine & New Materials (T/W engine = 183).
    - Boeing North American - Rocketdyne

Payload is 40,000 lbm. to LEO (100 nmi circular, 28.6 degrees) per reference 2, with 1.68 Mlb GLOW and 148.3 klb dry weight. [Note: 20,000 lbm. case also sized.]

This concept is an update on the Access to Space study Option 3 bipropellant all rocket single stage to orbit. The delta is the use of a new engine one generation beyond those proposed for the Reusable Launch Vehicle (RLV) program. This is defined in NAS8-39210. Additionally, new materials are used. The basic approach is to use advanced materials including nanophase aluminum, Si3N4, Cu-8Co-4Nb, graphite epoxy and C/SiC to increase component performance or decrease maintenance and improve life. The reference information for this concept is (1) Briefings to the HRST project on “Low Maintenance, Light Weight, High Performance Rocket Engine”, (2) Information package provided by request of the HRST Integration Task Force, Operations.

4. Horizontal Take-off, Horizontal Landing (HTHL) Ejector Scramjet (ESJ) Single-Stage-to-Orbit (SSTO).
    - Georgia Tech Aerospace Engineering, “Hyperion”

Payload is 18,000 lbm. to LEO with 662 klb GLOW and 106.5 klb dry weight. Transition to rocket is at Mach 10.

The concept has 5 ESJ engines plus 4 JP powered turbofans for loiter on return capability. The configuration includes non-integral tanks with multi-lobe tankage for LH2 and multiple tanks for LOX. The reference information for this concept is (1) Briefings to the HRST project including “Hyperion” briefing by Dr. John Olds, John Bradford, Laura Ledsinger, Mike Lee, David McCormick and David Way of Georgia Tech Aerospace Engineering, Aerospace Systems Design Laboratory.

4. Two-Stage to Orbit (TSTO), Vertical Take-off, Horizontal Landing (VTHL) All Rocket (Reusable Booster & Orbiter).
    - Langley Research Center TSTO, Vehicle Analysis Branch

Payload is 40,000 lbm. to LEO with a combined GLOW of 3.029 Mlb and booster and orbiter dry weights of 127 klb and 120 klb respectively. [Note: The 20,000 lbm. case is also sized with 2.294 Mlb combined GLOW and booster and orbiter dry weights of 102 klb and 99 klb respectively].

The evaluation here will be done for the 40,000 lbm. case.

The concept is a TSTO with identical LOX/kerosene engines on a 3-engine orbiter and a 6-engine booster. All engines fire at lift-off and propellants are cross fed into the orbiter. The staging is at mach 3 with the orbiter fully loaded. Booster return is a glide back (unpowered). Tanks are Al-Li, integral. Structures use composites primarily. Technology needs are similar to the baseline Access to Space concept (EMA's, high power density fuel cells, longer life engines). The reference information for this concept is (1) Information package provided by request of the HRST Integration Task Force, Operations.

4. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit Liquid Air Collection and Enrichment "LACE" Ejector Ramjet / Scramjet
    - Langley Research Center SSTO, Vehicle Analysis Branch

Payload is 24,000 kg (52,800 lbm.) to 100 nmi, 28.5 deg with a TOGW of 1.0 Mlb and a dry weight of 244 klbs.

The concept is a HTHL SSTO airbreather with 2 airbreather engines and 2 rocket engines (linear aerospike). Each airbreathing engine has 130 klbs of thrust at take-off. The 2 linear modular aerospike engines each have 117 klbs of thrust at take-off. The ejector ramjet and rockets are used for takeoff on the runway. The rockets are switched off at Mach 1.8 and all ramjet mode is initiated at Mach 3. Scramjet begins at Mach 6 and is in full scramjet at Mach 7.5. At Mach 15 departure from the 2000 psf isobar occurs as the vehicle pull-up occurs. This signals the start of LOX augmentation through the scramjet and the restart of the rocket system. Scramjet main engine cutoff is at Mach 24. Similar thrust of the airbreather and rocket engines does not equal similar ascent energy - the airbreather flowpath provides 83% of the total ascent energy. The LACE system and the engine rocket system (ERS) are used for low speed operation through transonic operation. Active cooling is required. Slush hydrogen is used. The reference information for this concept is (1) Information package provided by request of the HRST Integration Task Force, Operations, (2) Propulsion and vehicle worksheets provided to the HRST project and (3) baseline information from the Access to Space Study.

4. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit Magnetohydrodynamic Energy Bypass and AirSpike Virtual Effects Vehicle
    - ANSER w. Lockheed Martin Skunkworks
    - **NOTE: The ANSER concept was not fully assessed by the Ops Team due to discrepancies in the data format provided by ANSER and that required by the Ops Team**

Two technologies candidates in addition to the basic rocket based combined cycle propulsion for an airbreather vehicle are (1) magnetohydrodynamics and (2) virtual effects via a microwave beaming airspike.

Magnetohydrodynamics extracts energy from the rocket exhaust in order to generate electric current which is used to ionize a small percent of the secondary air flow (bypass, air ducted). The electrical energy is further used to accelerate the ionized airflow transferring energy and momentum back into the flow. Potential benefits include the ability to obtain ratios of air augmentation to primary rocket flows that are significantly larger than currently foreseen in ducted rocket approaches. Use of superconducting materials for the magnet technology, assuming synergy with the availability of liquid hydrogen on these systems, may be used to arrive at compact designs that allow high payload mass fraction concepts (as high as 10 percent of the vehicle as payload).

Airspike technology uses a similar extraction of energy from a rocket exhaust to ionize air in front of the vehicle. Once this energy transfer occurs the flow pattern around the vehicle can be altered to reduce drag. Potential benefits include the ability to use airbreathers with scramjet cycles or in general greater air augmentation before transition to rocket mode and pull up without the attendant disadvantages of active cooling requirements on areas such as the nose, leading edges, compression ramps or forebodies. The structure may be operated at a high transition to rocket Mach number but it may be designed as if it was “virtually” a low mach number vehicle.

Other concepts: Multiple other concepts, such as sled assisted rocket concepts, were also assessed in varying degree using tools such as COMET, OCM and PrOpHET.

APPENDIX C - Assessment using "A Guide for the Design of Highly Reusable Space Transportation".

(Edgar Zapata / Kennedy Space Center)

INTRODUCTION

The objective of this assessment is to provide operational insight toward the NASA Highly Reusable Space Transportation (HRST) study goal of identifying concepts and associated technologies that will enable open ended commercial growth in space transportation. This goal is linked to achieving recurring costs in the range of $100 per pound of payload.

METHOD

The method used in this assessment is a set of criteria derived from the Space Propulsion Synergy Team (SPST) document "A Guide for the Design of Highly Reusable Space Transportation" which was produced for the HRST project.

These criteria are dual fold - benefit and programmatics. Benefit criteria relate directly or indirectly to the issue of recurring cost, the operation of the system, it's dependability, environmental compatibility, public support, responsiveness and safety. Programmatic criteria relate to non-recurring cost issues of research and development (R&D) and the acquisition of the system by an eventual commercial operator. These issues are primarily about one time cost, risk and time.

A criteria matrix (Figure 1) was used to evaluate multiple HRST concepts that encompass various technology architectures and combinations of technologies. This method is a comparative, relative system that provides a qualitative ranking of the concepts separating along an X-axis and a Y-axis which correspond to cost and benefit respectively.

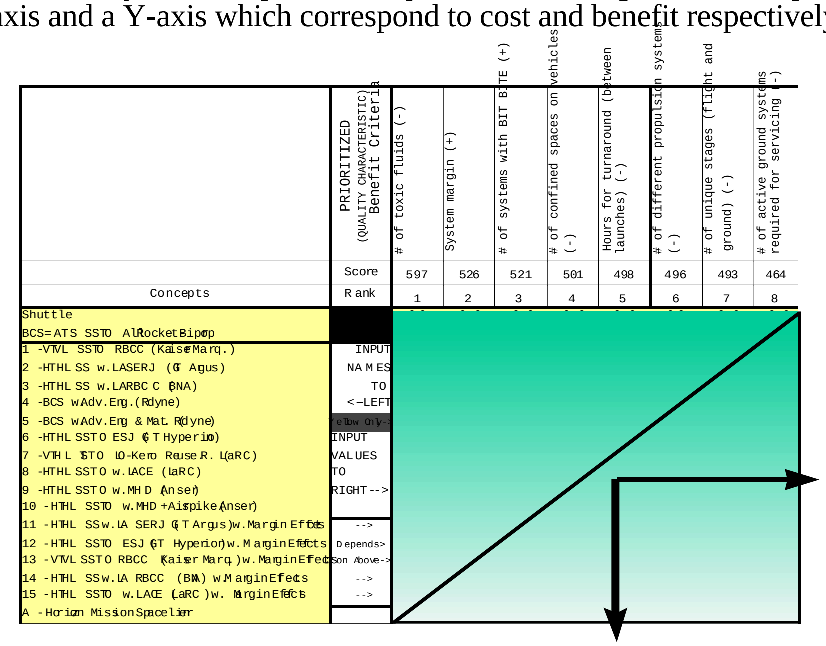


FIGURE 1: Section of the matrix correlating concepts against benefit criteria. A similar matrix is used for programmatic criteria.

APPROACH

The Shuttle is taken as the reference target for improvement. To further understand degrees of improvement the Access to Space Option 3 All Rocket SSTO (bipropellant version, 2.48 Mlb GLOW, 233 klb dry weight, 45,000 lb to 100 nm, circ. 28.5, using 7 evolved SSME's) is taken as a baseline for comparison.

Benefit

To simplify, only the first 29 measures from the SPST guide are used here. Scoring is done on a zero to 10 system. The Shuttle is scored as a "zero" in most of the criteria . Concepts are then measured by how much improvement they represent over the Shuttle in each criteria used. For example, one criteria in the SPST guide may list 10 related areas for improvement. If the concept represents an improvement in 5 of 10 of those areas the score would be a 5 for that criteria. An improvement in 4 of 7 areas would be a 4/7*10 or 5.7 score.

Programmatics

To simplify, only the first 9 measures from the guide are used here. For a "Shuttle" operation the development of new systems is not required, only purchase and subsequent installation and operation. For new concepts the score is heavily determined by considering new technologies and challenges as well as current readiness of integration toward full scale applications. A 10 will be a positive indication of a low cost to develop or to buy - basically an available system. A zero will indicate entirely new, multiple, undeveloped systems are required for the concept.

RESULTS

The charts that follow, Charts 1-5, layout the concepts considered.

Proper interpretation of Charts 1-5 must account for the following assumptions and approach:

- Where "Shuttle" is referred to the scenario being considered is that in which a duplicate operation and capability were to be procured by a private entity. The same applies to the baseline Access to Space concept and all the other concepts.
- All measures are relative. Notable steps or differences on the unit scales are of interest in determining potential toward achieving HRST goals as well as in determining the path of least risk and cost toward HRST goals.
- Concept level information firmly establishes some of the measures required by this method. If a criteria (Ref. "A Guide for the Design of Highly Reusable Space Transportation" by the Space Propulsion Synergy Team) was at a level of detail where the information was unavailable then relative assessments were used relying on expert judgment.

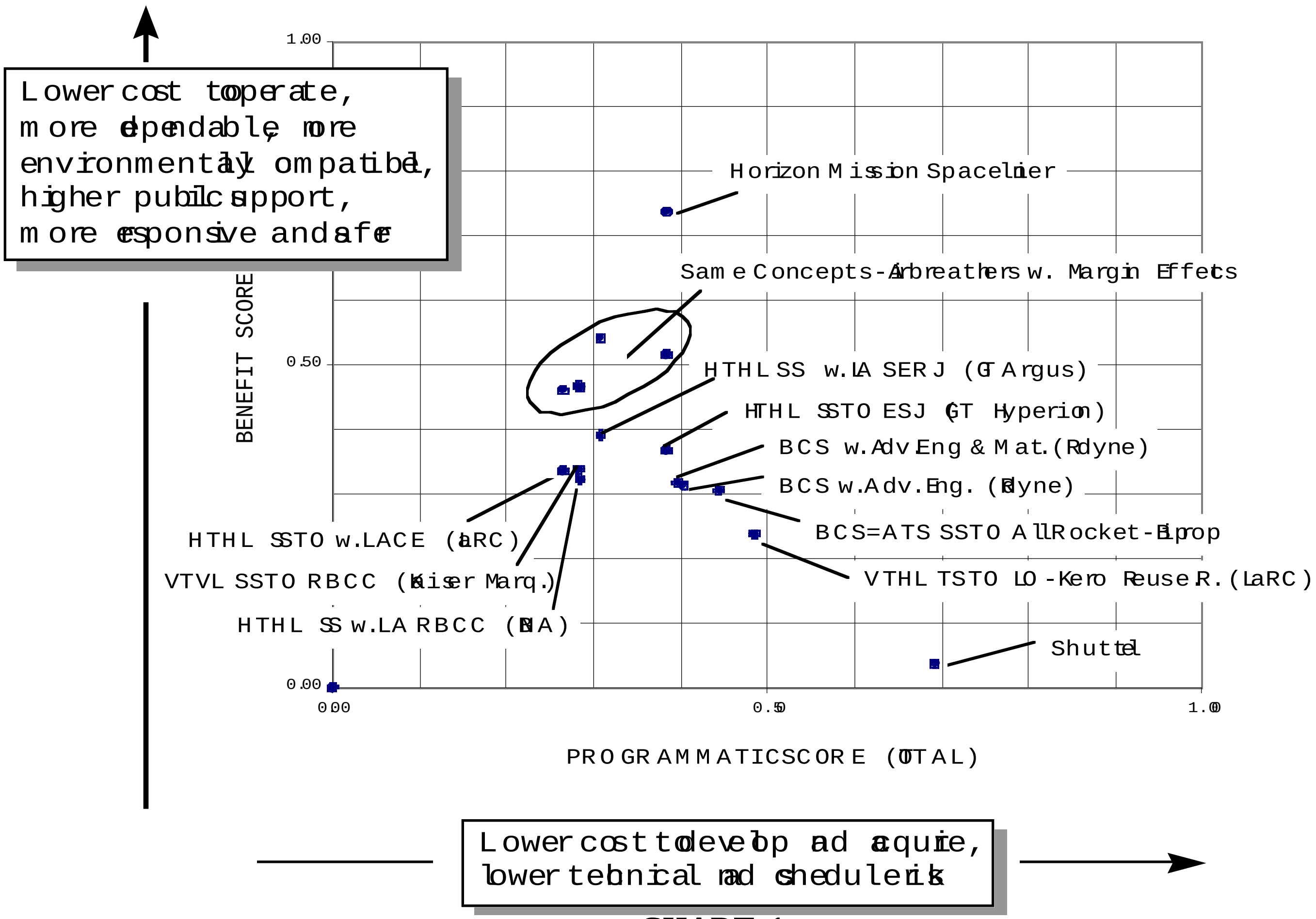
Chart 1 summary: The points resulting from a total benefit and programmatic assessment resulted in a layout with Shuttle as the low point, on benefit, and farthest to the right, near and available, albeit at a price. This is an artifact of Shuttle as the reference for improvement. Of note the TSTO was shifted over in risk and cost almost as much as the baseline Access to Space SSTO. Both represented significant improvements in benefit. Advanced propulsion increased risk and cost on the rocket SSTO without a similar increase in benefit (the advanced BCS concepts). The airbreather "Hyperion" represented a more proportional benefit to risk increase. Assuming margin translates into operability gains, the "Hyperion" type concept took a step function leap in benefit (point farthest to the right in the circle "Same Concepts-Airbreathers-w. Margin Effects"). The other airbreather concepts also improved significantly over rocket only systems assuming margin benefits (Ref. Section "Non-Linear Technology and Cascade Effects"). Room for improvement exists on airbreathers as evidenced by a hypothetical best case, the Horizon Mission spaceliner.

<u>Chart 2 summary</u>: The points here have equal benefit ratings as the prior but the **R&D** criteria of risk and cost were the only programmatic considerations (Ref. "A Guide for the Design of Highly Reusable Space Transportation".) The points <u>expand</u> from the previous chart along the X-axis. This indicates the concepts have very distinct levels of research and technology required to become viable systems ready to integrate, acquire and operate. Shuttle moved even farther right as an indication of no R&D required to bring to fruition since all has been developed for this operational system (albeit little benefit, i.e. high cost per pound of useful payload). A clear distinction also occurs between rockets and airbreathers versus Chart 1 where the points were closer together. This reflects the required advances in airbreather technology R&D which may require many of the same technologies required by rocket approaches in addition to major advances beyond rocket approaches such as in propulsion.

<u>Chart 3 summary</u>: The points here have equal benefit ratings as the prior 2 charts but the **acquisition** criteria of risk and cost were the programmatic considerations (Ref. "A Guide for the Design of Highly Reusable Space Transportation".) The points <u>contract</u> indicating that if a moderate TRL level of 6 or more is achieved for the required technologies, and that a private entity then does not have to make this R&D investment, that the airbreather concepts such as Hyperion become more competitive than rocket single or two stage reusable systems. However, the more complex airbreather concepts do not become competitive here either due to launch assist infrastructure, complex engines or complex vehicles - all affecting acquisition.

<u>Chart 4 summary</u>: This assessment is of special relevance to HRST goals. Here acquisition criteria, just as previously, were the only programmatic considerations. The scenario assumes the basic R&D is complete, including demonstrators, as well as an additional step not taken previously. This next step is the actual demonstration of orbital capability as well as some basic operational experience. The private entity acquisition is reduced in risk and cost since implementation becomes private operation of a duplicated system allowing for 2nd generation improvement technically as well as efficient private enterprise operation. Here Shuttle has transitioned to the left most position on the chart. This reflects unacceptable cost of acquisition. The simpler infrastructure, simpler vehicles move to the right (such as Hyperion). The complex vehicles occupy a middle space. The complex vehicles with complex infrastructures occupy the far left near Shuttle, albeit at higher benefit. The indication is that much improved systems (highest up) can be achieved at low cost and risk (farthest right) . The benefit would drive the choice to simple systems with low infrastructure such as HTHL SSTO systems. This chart is also of special relevance assuming different avenues of participation for R&D versus acquisition. It may be assumed per HRST guidelines that basic R&D is invested by the public sector leaving only acquisition and operations costs and risks for the private sector.

<u>Chart 5 summary</u>: This is a pareto summary of the benefit and programmatic scores from Chart 1. This allows a combination visualization of benefit and cost as one measure rather than two. The usefulness of this chart is in broadly comparing concepts against each other.



Lower cost to operate, more dependable, more environmentally compatible, higher public support, more responsive and safer
BENEFIT SCORE
1.00
0.50
0.00
Horizon Mission Spaceliner
Same Concepts-Airbreathers w. Margin Effects
HTHL SS w.LA SERJ (GT Argus)
HTHL SSTO ESJ (GT Hyperion)
BCS w.Adv.Eng & Mat.(Rdyne)
BCS w.Adv.Eng. (Rdyne)
BCS=ATS SSTO All Rocket-Bi prop
VTHL TSTO LO-Kero Reuse R.(LaRC)
Shuttle
HTHL SSTO w.LACE (LaRC)
VTVL SSTO RBCC (Kaiser Marq.)
HTHL SS w.LA RBCC (BNA)
0.00
0.50
1.00
PROGRAMMATIC SCORE (TOTAL)
Lower cost to develop and acquire, lower technical and schedule risk

CHART 1

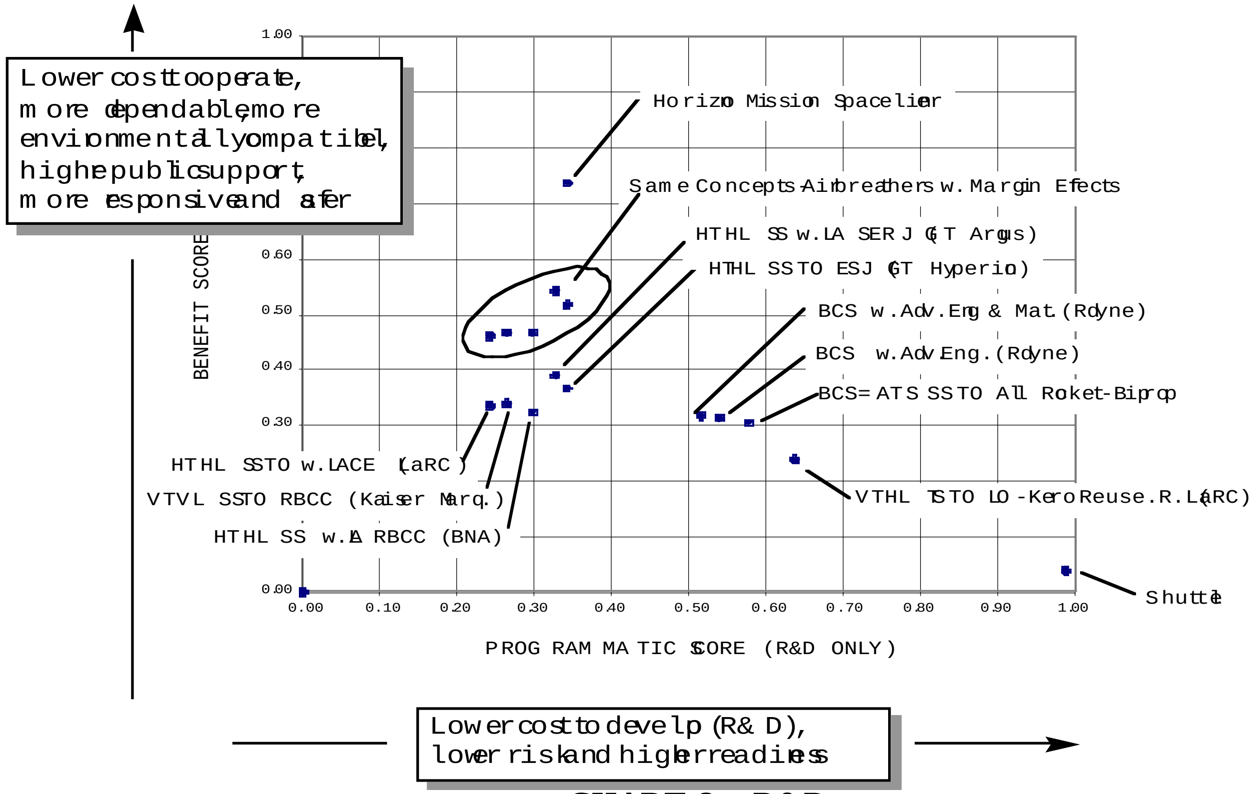


CHART 2 - R&D

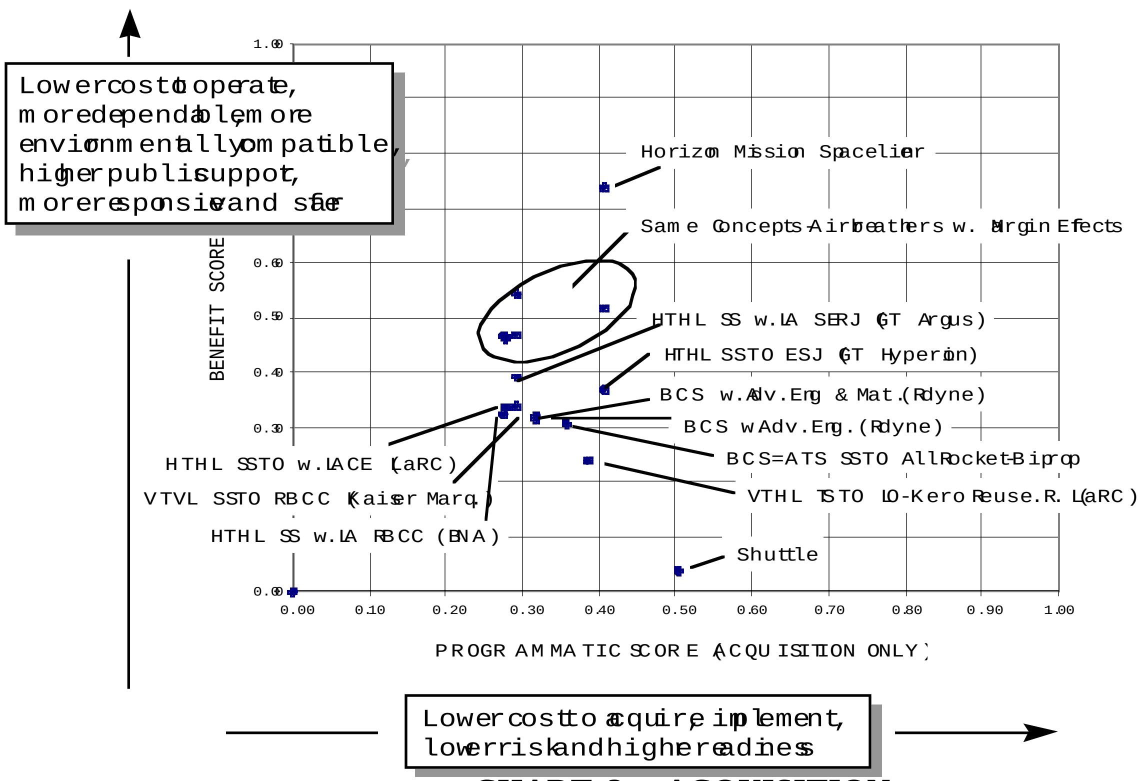


CHART 3 - ACQUISITION

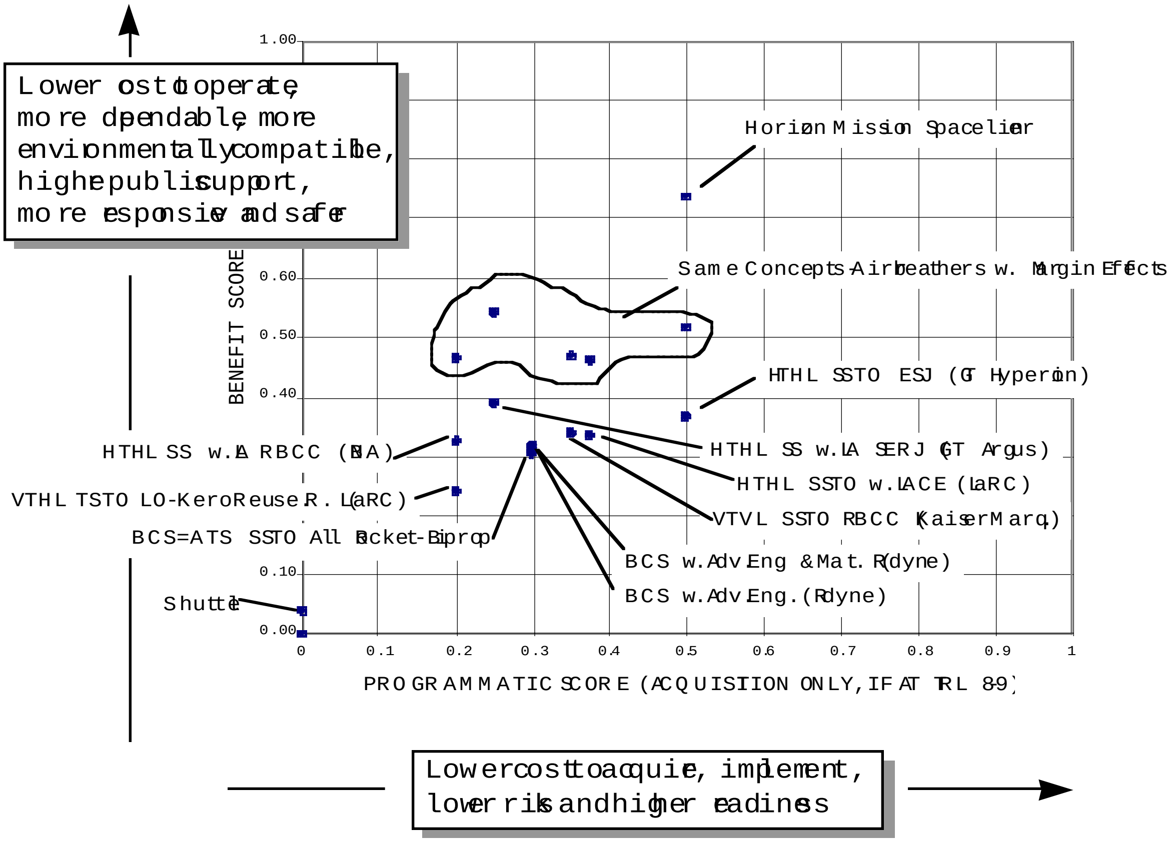


CHART 4 - ACQUISITION IF AT HIGH TRL

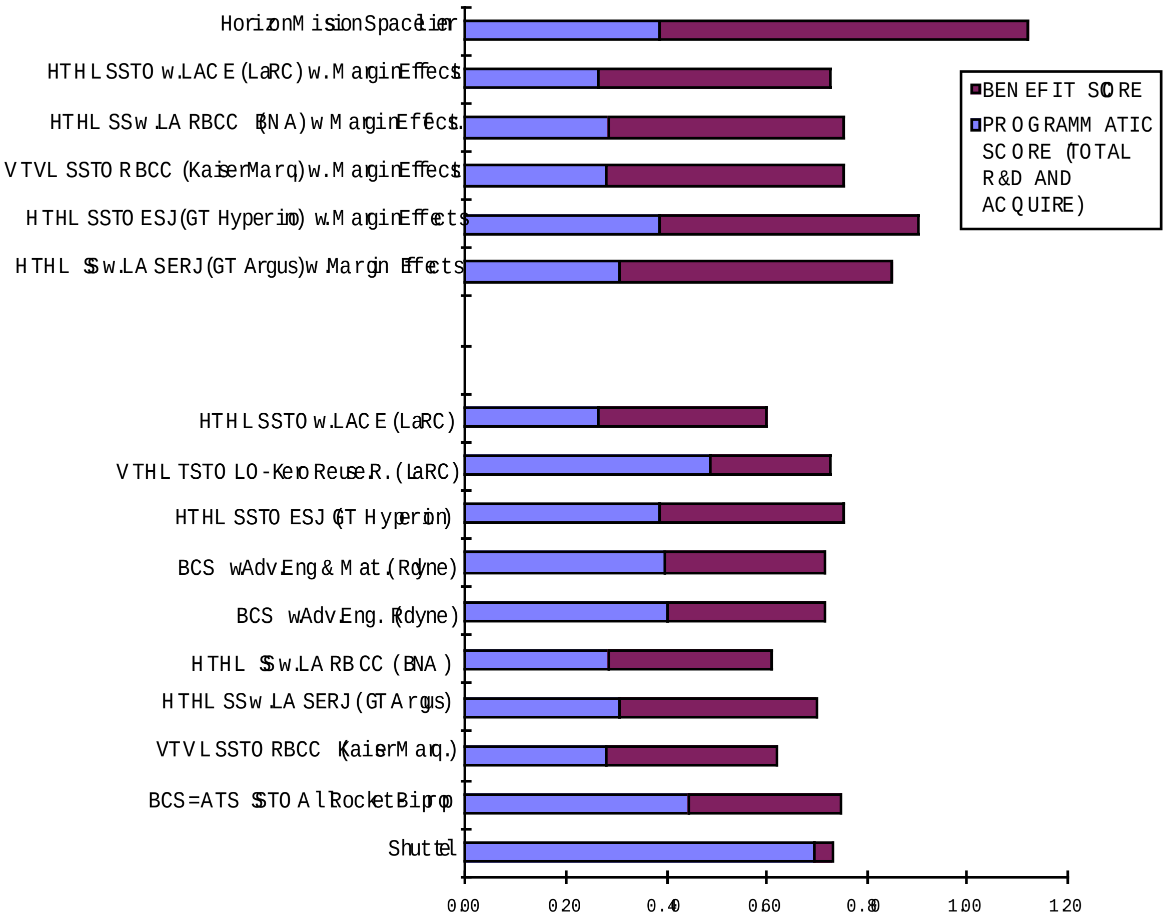


CHART 5 Pareto Summary of Benefit and Programmatic Scores

SUMMARY

1. Conceptual level information has been qualitatively assessed.
It is intended in this assessment to provide a qualitative answer to the questions “what are the concepts with *potential* to achieve recurring costs of $100 per pound of payload” and “what are the technologies and associated costs / risks of development these concepts require”? The method used here is based on a process which structures around measurable criteria and priorities and is especially suited to early conceptual, creative phases of design decision making.

2. Multiple concepts architectures have been assessed.
The concepts assessed here encompass a broad range of possible future space transportation systems. The benefits of these from a recurring cost, operational perspective, the view a commercial operator would be most interested in, have been assessed relatively from concept to concept. The economics of R&D have been separated from the economics of acquisition since these represent, for the HRST study, different sources in investment, public or private.

3. Designs have been related to eventual operations issues as well as near term decision making programmatic issues (i.e. cost/payoff).
The relation of a design feature or technology to (1) it’s immediate impact such as R&D, basic test or demonstration, and to it’s (2) far term impact such as integration, activation, acquisition and flight and ground operations and responsiveness has been the focus of this assessment. Increases in complexity have been balanced against potential gains not related to payload, but rather related to low cost operations, responsiveness and potential aircraft like operations benefits.

CONCLUSIONS AND RECOMMENDATIONS

1. Airbreather type, rocket based combined cycle (RBCC) approaches have significant potential benefit beyond rocket only type approaches.
The benefit of airbreather type approaches have in this assessment been established and *relatively* placed for various possible configurations. Benefit over rocket-only type concepts has been established for some but not all airbreather configurations.

Recommendation # 1: A demonstrator is required.
A demonstrator is required that scales up toward the proper flight regime and the more complex systems that may associate with rocket based combined cycle (RBCC) concepts. Anchoring the benefits of airbreather propulsion through demonstration will allow quantified understanding of the proximity to achieving the HRST operational objectives. Basic R&D, component, system and integrated testing focused on advanced propulsion development is required to sidestep inherent rocket only limitations.

2. Airbreather-type, RBCC approaches offer the only <u>near term potential</u> toward achieving HRST objectives of cheap access to space at about $100/lb. of payload.
As shown in Chart 1, the airbreather approaches, with margin gains considered to have a distinct tie in to potential operability gains, have a notably higher benefit over other approaches. However, this occurs for concepts focused more squarely on operations as a driver. Other more far term concepts were not considered here since they would have been programmatically too far to the “left” as visualized in Chart 1. These included microwave beaming concepts and fusion devices.

3. Margin that does not translate into operability does not improve significantly over current systems.
As shown in Chart 1 not all airbreather concepts ranked equally. This is likely due to differences in the design focus around multiple variables. Margin as evidenced by required mass fractions twice or three times lower (better) than a rocket single-stage-to-orbit may be considered relevant only if it translates into operability *or* payload. It is proposed here that margin is only relevant if it translates into operability *and* payload with operability as more crucial. The potential of airbreathers is not likely to be demonstrated immediately in any attempt to gain significant payload combined with test and demonstration. It is more likely that as the technology evolves, if properly focused on recurring costs, capabilities beyond rocket reusable launch vehicles will be achieved in payload cost per pound and payload per year in the long term due to recurring cost improvements.

4. Margin benefits significantly differentiate airbreathers over pure rocket concepts. Margin benefits must be realistically understood, quantified, traced and manifest in all systems, propulsion and non-propulsion.
The doubling or tripling of the design space for an airbreather is oft quoted. Rather than $1/10^{th}$ of a take-off-weight as hardware for a rocket (with payload) the design space for an airbreather (with payload) expands to $2/10^{ths}$ or $3/10^{ths}$ of the take-off-weight. This is more aircraft like and heading in the right direction. Chart 1 establishes this distinction. Estimating that airbreather engines will occupy much more of that total weight than for a rocket propulsion concept, (some estimates place this at approximately 7% of take-off-weight) the remaining portion of structural mass fraction should benefit enormously. This remaining portion of structural mass fraction may still be twice as high as what a rocket concept can theoretically achieve. In practice however, other systems technology approaches continue to target weights consistent with current rocket approaches. Thermal protection systems (TPS) is an example of this - next generation TPS that applies to airbreathers are targeting weights below those of current Shuttle TPS.

Recommendation # 2: Future concept definition for airbreather space transportation systems must provide links to margin benefits.
Realistic estimates are required of resulting margins from airbreather approaches correctly accounting for additional systems unique to airbreathers such as active cooling, active geometries and associated actuation mechanisms, fans, etc. The effect of this margin on other systems such as TPS, structures, power and subsystems, flight and ground, must be further understood (Ref. Recommendation #1).

5. Launch assist recurring cost impacts require further understanding and quantification.
As shown on Chart 1 the concept ranked with the most benefit is the Horizontal-take-off-Horizontal-Landing (HTHL) single-stage Supercharged Ejector Ramjet (SERJ) with launch assist. This estimate is more uncertain given the lack of an operational database or group of expertise related to such a system; this uncertainty is additional to and larger than uncertainties on propulsion. Studies on similar systems can only assist is definition at the component level of similarity. Passenger rail systems are not applicable in the areas of experience with cryogenic fluid interfaces to or through a sled (versus just electrical power distribution), the dynamics of separation (versus transient fixed systems), the speeds at the high end for these concepts, the load distributions and the complexities of the sled itself (pitch up actuators, interfaces, fluid, electrical and structural). Complexities here are more similar to staged space transportation systems.

6. Launch assist where used to simplify a system, especially the vehicle, meant greater benefit moving toward HRST goals; where launch assist was used to reduce mass fraction or in combination with more systems, it resulted in little benefit over rocket systems.
As shown on Chart 1 there are two HTHL single-stage concepts with launch assist. One (referred to as "Argus") ranked significantly better on benefit than the other and slightly better on R&D programmatics.

7. The nearest term airbreather in cost and risk, with significant benefit over all other concepts, was a single-stage-to-orbit HTHL using an ejector scramjet (ESJ).
As shown in Chart 1 an SSTO HTHL with ESJ (referred to as "Hyperion") represents the nearest term concept with a significant improvement over rocket concepts. The basic technology common to airbreathers is the ejector-ramjet and ejector scramjet-cycles. A concept with no fan avoids fan deployment and stowage issues; however, it does not avoid active cooling issues, also common to most concepts. The potential to avoid active cooling issues would have resulted in even greater benefit assessment (a positive factor in the HTHL "Argus" concept).

Recommendation # 3
Two major systems areas require technology development, propulsion and thermal protection (highly linked for airbreather concepts). For commonality with multiple avenues, and with enabling benefit they become priorities:

- **Ejector ramjet (ERJ) R&D and demonstration.**
- **Ejector scramjet (ESJ) R&D and demonstration, build on previous.**
- **Thermal protection systems (TPS) - passive, zero waterproof, robust against damage.**
- **Thin leading edge passive TPS.**
- **Thermal protection systems (TPS) - active, robust, low maintenance (as fallback).**

Active cooling should compete in this priority in so far as it is requisite; passive cooling developments should focus on the potential elimination of any active cooling requirement at leading edges, inlets and at other structures as required. Active cooling should be considered a backup or fallback technology.

8. Leverage off of Reusable Launch Vehicle (RLV) rocket type technologies to further the programmatic and operational maturity of airbreathers.

Certain technologies are common and priorities for both rocket only type reusable launch vehicles as well as airbreather type space transportation systems.

Recommendation # 4

- **Reusable propellant tankage and feeds (cryogenic service) - composites.**
- **Integral, conformal propellant tankage (for all propellants).**
- **Robust, maintenance free thermal protection systems.**
- **Electric actuation, high horsepower - eliminate hydraulics, applies to propulsion geometry and aerosurfaces.**
- **Power systems, simplified, non-toxic, low and high horsepower - eliminate hypergols, eliminate multiple different types of power systems to service and maintain.**
- **Common propellant systems (propellant grade fuel cells, orbital maneuvering systems (OMS) and reaction control systems (RCS) using propellants common with main propulsion).**
- **Vehicle and ground health management systems (VHM/HM).**

9. Priority technologies focused on operations differ from some current directions. The following areas require emphasis:

- **TPS development <u>without</u> aeroshells & purges:** The development of passive, robust, zero coating, zero waterproof, zero purge TPS is priority.
- **Engine count is a key, simple measure of potential benefit, focus on fewer:** Objectives should be between 2 and 4 main engines or modules. Fewer engines relates to multiple measures of benefit such as reducing confined spaces, which inherently require purges, servicing and interfaces to the ground as well as additional complex systems for leak detection and isolation. Engine count also relates to key issues of additional interfaces flight and ground, fluid and electrical, basic issues of reliability and dependability (more parts, more opportunities for failure, more maintenance), active systems, and functional complexity, flight and ground.
- **Horizontal vs. Vertical take-off:** The benefit of reduced infrastructure for vertical landing may represent a far term capability that is desirable for operating within infrastructure or location constraints. Aircraft, for example, have evolved both large passenger jets as well as urban centered helicopter services. For the near term, however, the ability to simplify space transportation as far as relates to engine count will be assisted uniquely by horizontal take-off. Assuming engine out requirements, the horizontal take-off uniquely allows both low engine count as well as ease of recovery and return to the spaceport. This is an area where rockets will not be able to improve on, high engine counts being required for engine out capabilities. Further, horizontal take-off rockets, especially single stages, are practically constrained

leaving vertical take-off options as most viable, which again entails high engine counts.

- **Focus on environmentally benign technologies:** Ground-rules for future system development should include no hypergols (propulsion or power). Also, avoid multiple toxic freons and ammonia. These relate directly to high operating costs, hazards and complex servicing and turnaround requirements based on Shuttle experience.
- **Avoid slush hydrogen** with unfavorable programmatic (non-recurring cost) impacts as well as unfavorable benefit (recurring cost) impacts. Facilities, infrastructure that is simple and responsive to high flight rates will not otherwise be enabled.
- **Hydrogen as common fuel:** Advances in non-rocket areas may benefit the ability to use hydrogen as a common fuel in systems such as the Hyperion HTHL SSTO turbofans (used for loiter and self ferry). This would eliminate separate JP fuel, possibly simplifying servicing, basic design and operation. This represents an avenue of future study to determine synergy potential with other work in Hydrogen energy applications.

10. Additions of complexity must be further quantified as to benefits.
As shown in Chart 1 the additions of systems such as fans, liquid air collection and enrichment (LACE), slush hydrogen and launch assist did not always mean greater recurring benefit. Neither did additions of complexity, adding capabilities such as loiter, thus eliminating a dead-stick glide-in landing, necessarily result in less recurring benefit (Example: HTHL “Argus” used a fan / supercharging approach). The benefits to be accrued from these additions were highly dependent on overall system configurations, how they are integrated into the whole concept and what they trade against. It is highly possible to have increasing complexity coupled with increasing economic viability as witnessed in today’s aircraft and airport infrastructures which are many orders of magnitude more complex than early aircraft in the pre-DC-3 era. The concept that integrates these complexities toward low cost operations is crucial to basic airbreather economic viability.

11. Viability (orbital capability, performance closure) is not assessed in this report.
A determination of a concepts ability to actually be implemented and succeed has not been a focus of this task which is operations assessment relating to recurring costs and commercial growth potential. It is assumed by the analysis here that the necessary performance of the concepts is established. Related to recommendation # 1, early basic R&D is required that establishes the theoretical predictive framework that allows proper assessment of potential concept performance viability.

12. Cost modeling for operations and life cycle focused on conceptual phase type information is required.
Recommendation # 5
The conceptual phase of any study activity is characterized by broad characterization and less specific information. By it’s nature the intent is to avoid allocating into a program before preliminary study has been undertaken. Cost modeling with an ability to work on limited types of information is required. Models based on more specific information have also been noted as an area for agency improvement since even operational systems such as Shuttle do not adequately account for and explain costs of operations with any traceability that allows decision making focused on improvement.

13. The two highest benefit concepts had less than 40 klb payloads yet may have sufficient benefit to realize greater payload per year.

As shown in Chart 4, assuming acquisition at a mature technology level, the Hyperion concept was the nearest term system to acquire (low infrastructure, simpler vehicles). Significantly, this is in comparison to a Shuttle type system which is far to the left. However, the Hyperion HTHL SSTO and the Argus HTHL with launch assist were the only two systems assessed here that had less than 40 klb payloads. The addition of infrastructure for the Argus case represented only a 2k payload gain (20k versus 18k to LEO for Hyperion). The LACE system HTHL SSTO represented a 2nd near term option but with over 50 klb payload to LEO. Further assessment is required that equalizes these systems to a throw weight capability.

Recommendation # 6

A measure "useful payload per year to LEO per vehicle" is proposed as an equalizer that allows the benefit of systems with less payload but more response (flight rate at a given resource expenditure or cost) to be measured against systems with less response and higher payload. The ideal is more payload as well as higher flight rate. Less payload per flight should not be assumed to be undesirable except as applies to particular markets.

14. Do not underestimate the potentially large recurring economic impact of closed compartments on cryogenic vehicles.

Future system features such as purged aeroshells, TPS purges, multiple separate tanks in order to conform to certain moldline approaches, and multiple engine modules should not be underestimated in the degree to which the resulting required infrastructure can be non-responsive. Numbers of interfaces, numbers of active systems required to operate safely, numbers of strict requirements on flowrates and temperatures, numbers of detection systems and measurements, and numbers of failure modes or opportunities for failure are all negatively affected by these types of approaches.

15. Room for improvement exists.

As shown in Charts 1-5 the ideal spaceliner (Horizon mission) is an even more dramatic improvement over the systems conceptualized for this study. Iteration toward this improvement is possible with existing concepts.

16. Magnetohydrodynamics (MHD) and air spike technologies offer potential for operability benefit.

MHD and airspike concepts were not assessed against the SPST guide. Broadly considered only as technologies against the guide benefit criteria potential favorable affordability benefits exist.

Basic laboratory scale tests of magnetohydrodynamic phenomenon can build on basic demonstration of rocket based combined cycle concepts. Roadmaps are required here that may allow MHD to determine basic feasibility as well as to improve in theoretical understanding while not being immediately dependent on RBCC development. The operability and any benefit of the system will be determined by (1) developments in superconducting materials toward becoming dependable, reliable flight systems, (2) the operability of the fluid system if using liquid hydrogen and (3) advances in passive TPS so as to avoid combinations of active fluid cooling systems as well as expanded active fluid cooling of the propulsion MHD magnets.

The air spike technology, focused as a potential fallback technology to avoid active cooling requirements on vehicles also offers potential for operability gains. As with previous concepts considered, final configuration into a unique concept approach may or may not take optimum advantage of a technology in terms of HRST goals.

NON-LINEAR TECHNOLOGY AND CASCADE EFFECTS

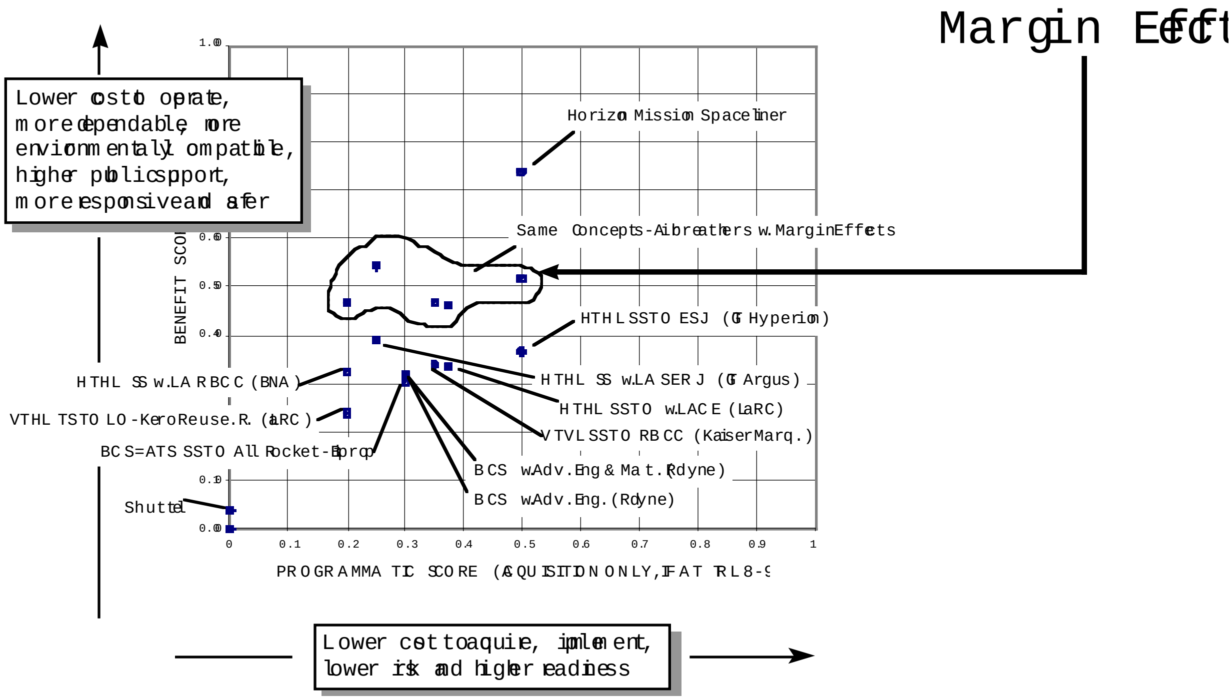
The complexity associated with improved capability is exemplified in the transition from the earliest of aircraft to the DC-3 of the 1930's. Increased complexity was far outpaced by increased capability and commercial affordability. A productivity was associated with new, additional systems which paid for themselves.

Assumption: Doubling and tripling the system which a designer has available to work with (3/10^{ths} of the "system" as vehicle versus 1/10th) will have a cascade effect that outpaces increases in complexity in a high exponential relationship. Rocket systems are not considered in this check due to inherent limits on margin gains.

Affect (increase) the following AIRBREATHER criteria ratings by doubling:

2-System margin
3-Number of systems with BIT/BITE (VHM potential)
5-Hours for turnaround
10-Number of components with demonstrated reliability
13-Percent of propulsion automated (VHM potential)
14-Number of hands on activities required
16-Technology readiness levels
22-Number of checkouts required
24-Number of inspection points
25-Number of propulsion systems with fault tolerance
28-Number of labor hours on system between on/off cycles or use

The effect of the assumption of more margin as being used to benefit the operability of the system is shown in Charts 1,2,3 and 4 in the outlined sections tagged "Same Concepts-Airbreathers w. Margin Effects" (example shown below). Notable improvement occurs in step function format over all non-airbreather concepts when rating against benefit criteria. Programmatic issues are assumed unaffected (points above line up with points below, same position on the programmatic X-axis).


Margin Effect
Lower cost to operate, more dependable, more environmentally compatible, higher public support, more responsive and safer
Horizon Mission Spaceliner
Same Concepts - Airbreathers w. Margin Effects
HTHL SSTO ESJ (GT Hyperion)
HTHL SS w. LA RBCC (BNA)
HTHL SS w. LASER J (GT Argus)
HTHL SSTO w. LACE (LaRC)
VTHL TSTO LO-Kero Reuse. R. (LaRC)
VTVL SSTO RBCC (Kaiser Marq.)
BCS=ATS SSTO All Rocket
BCS w. Adv. Eng & Mat. (Rdyne)
BCS w. Adv. Eng. (Rdyne)
Shuttle
BENEFIT SCO
1.0
0.6
0.5
0.4
0.1
0.0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
PROGRAMMATIC SCORE (ACQUISITION ONLY, IF AT TRL 8-9
Lower cost to aquire, implement, lower risk and higher readiness

HORIZON MISSION SPACELINER

To understand the degree of possible improvement against any benefit criteria a high payoff, idealized spaceliner and spaceport are assumed that enable broad based, high growth commercial operations.

This concept is then evaluated against the benefit criteria outlined by the Space Propulsion Synergy Team. The programmatics are taken as similar to the HTHL SSTO “Hyperion” concept summarized previously.

Definition

Essentially the Horizon Mission Spaceliner is a space transportation system - vehicle and ground - with very high margin (as in robustness, long life and true “use and forget” reusability), few different fluids, none toxic, and with ease of ground servicing (propellants but few if any purge requirements) and a low engine count (about 3 or 4 for the sum of any main propulsion and orbital maneuvering system). Intelligence is high making avionics one of many systems (fluids, structure, engines…) with sophisticated health monitoring and fault isolation.

The spaceliner has very few different fluids and few toxic fluids. There are no hypergols, no hydraulic fluid or ammonia. Additionally, only one low toxicity commercially common coolant is used, not various, where fluids are required for thermal management such as in cooling loops.

Margin is high. Propulsion has evolved to where mass fraction gains have benefited systems other than just engines and integration issues. Thermal protection is passive and only some robust parts of the propulsion system require active cooling. Ram and scram are included however loiter capability is achieved with no additional fluids and tanks.

The vehicle lands within weather constraints no different than commercial aircraft. The landing gear is robust and properly sized to allow many flights without anything more than a walk-around prior to takeoff. The integrated health management in both ground and flight systems automatically detects any faults and isolates them to the source. Maintainability is high, quickly repairing any fault in minutes. Supportability is high, with few faults occurring, if any, from flight to flight.

The operability of the vehicle is high - designed for few support needs there are few confined spaces requiring purges, leak detection and leak isolation systems. Engine count is low. Cryogenic systems have converted more margin into well insulated purge free systems. Should access be required, margin is sufficient that doors were designed in that easily open via quick release and even motorized panels that self lock in minutes.

The high margin also allowed robust tanks that do not complicate loading of propellants or create many failure modes. The umbilicals easily self connect since vehicle interfaces have now become robust and allow easily engineered automated connect and disconnect of umbilicals for loading and replenishing any hazardous consumable. The hazardous operation is monitored by a few individuals in the spaceport who also monitor other systems in service simultaneously.

The reliability is high. Structure has the proper margin so no inspections are required for sensitive structure due to moisture or cycles.

The vehicle has little to integrate with on the ground. Interfaces are few.

The number of engines has diminished as propulsion advanced in thrust to weight while still being reliable in flight as well as operationally reliable on the ground. The vehicle operates with no range constraint such as explosive systems in case of malfunction. This has been enabled by iterative certification on designs. As required, with an operability focus, system problems in development were redesigned to meet stringent certification requirements such as the ability of engines to cycle on and off reliably dozens of times with no user intervention in between cycles. Extended duration tests also followed the same focus.

The vehicle does not require many ground systems. The vehicle is loaded and can immediately takeoff. The operation does not require exotic ground support nor create hazards at takeoff from gases and residuals. All hazards have been vented away from the vehicle since margin has allowed the addition of extended vent lines on board through the same interfaces used for loading. Boiloff hazardous gases are safely burned far from the takeoff site. As the vehicle completes final preps a health management system confirms a “go” or “no-go” condition. No operator is required to verify specific valve configurations nor to recover - in most all instances recovery is automatic. A virtual pilot back at the station handles specifics of a spaceliners state of readiness. Operator intervention is usually limited to flight runway type operations redirecting traffic as required.

Concepts and Technology Matrix

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
Access to Space Bi-prop, SSTO ***(reference only)***	40	233	0.90	1	61	418	n/a	• Rocket • **7 main engines (evolved SSME) & 2 OMS engines** • **Al-Li LOX/LH2 tanks** • Electromechanical Actuators (EMA's) • No hypergols
Kaiser Marquardt VTVL SSTO	40	185	0.762	2	15-20	104.2	12	• **Vertical landing** • **Fan (Supercharging),** • **Multiple non-integral LOX tanks** • Integral LH2 Tank • **Ram** • **Scram - SESJ** • **Active Cooling** • **12 main engines & 4 OMS engines**

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
Argus HTHL w. Launch Assist	20	76.4	0.83	1	20-23	209	6	• **Launch assist** • **Fan (Supercharging)** • Integral graphite/PEEK honeycomb tanks w.metal liners • Ti-Al/Si-C hot structure • Ultra-high temperature ceramic (UHTC) TPS (>3000F); metallic TPS (large block inconel); TABI (blanket insulators) passive TPS • No active cooling, all passive TPS • High power density fuel cells • EMA's • Pods / engines • **Ram - SERJ** • 2 main engines & 2 OMS engines

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
BNA HTHL Waverider w. Launch Assist	40	212.1 (Note: vs. Argus 76.4 w.20k to LEO)	0.75	1	22	72	>10	• **Launch assist** • Multiple tanks, waverider configuration packaging • Active cooling • **RBCC** • **8 main engines with dual use as OMS**
BCS w. Adv. Engine	40	182	0.90	1	92	421	n/a	• Rocket • Full Flow Staged Combustion • **Ox-Rich** • **Simplified turbopumps (SLIC based)** • **Jet pumps** • **Laser ignition** • **Hydrostatic bearings** [Note: all applicable to RBCC/ ejectors]

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
BCS w. Adv. Engine and hi-T/W	40	148	0.90	1	183	421	n/a	• Same as prior plus: **Nanophase Al, Si3N4, Cu-8Co-4Nb, GrEp, C/SiC** • **Reduced parts manufacturing, engine**
Hyperion HTHL SSTO	18	106.5	0.81	1	28	79.5	10	• **Multiple non-integral Graphite/PEEK tanks w. liners** • Ti-Al wings w. Ti-Al/Si-C structure • Ultra-high temperature ceramic (UHTC) TPS (>3000F) • **Active film cooling of fore-body and nozzle** • High power density fuel cells • EMA's • Advanced avionics • **Ram** • **Scram - ESJ** • **5 main engines & 2 OMS engines & 4 turbofan engines**

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
TSTO LOX / Kerosene	40	Orb: 120 Boost: 127	<0.90	1	MA-5 based.	MA-5 based. (Note: MA-5A thrust 423k)	n/a	• Rocket • **9 main engines & 2 OMS engines (all LOX / kerosene)** • Integral Al-Li tanks • High power density fuel cells • EMA’s • Composite structures • No TPS on booster • Light-weight materials (Silicon Nitride, composites…) for engines.

Concept	Payload (klbs to LEO, 100nm, 28.5 circ)	[1]Dry Wt (klbs)	PMF	EOC	T/W_e	Engine klbs Thrust (sea lev.)	Mach Trans. Rock.	**Unique Technology Challenges**
SSTO HTHL w. LACE	53	244	0.70	1		Airbr. 130k, Rock. 117k	15	• **LACE - Liquid Air Collection and Enrichment** • **2 airbreather engines & 2 linear aerospike rocket modules (dual use as OMS)** • 2D variable geometry for ram/scramjet • **Integrated TPS and thermal management system (active cooling)** • **IMI TPS system with purge** • **Flight weight non-integral cooling panels for engine** • All composite fuel system • **Slush hydrogen** • Conformal integral GrEp SH2 tank • **Rotating wings** • **8,000 psi hydraulic system**

PMF = propellant mass fraction (propellant as fraction of total hardware including payload)
EOC = engine out capability **T/W_e** = engine thrust to weight **1** = dry weight not counting payload and misc. **SESJ** = supercharged ejector scramjet; SERJ = supercharged ejector ramjet; ESJ = ejector scramjet

APPENDIX D - Conceptual Operations Manpower Estimating Tool (COMET), Operations Cost Model (OCM)

(Mike Nix / Marshall Space Flight Center)

1.0 OVERVIEW

"FINDING 4: IF THE FEDERAL GOVERNMENT WISHES TO INVEST IN NEW OPERATIONS TECHNOLOGIES, IT SHOULD HAVE CLEAR LONG-TERM GOALS AND A WELL-DEFINED PLAN FOR DEVELOPING AND INCORPORATING NEW TECHNOLOGIES IN SPACE TRANSPORTATION OPERATIONS. SUCH A PLAN MUST BE BUTTRESSED BY DATA FROM NEW AND MORE RELIABLE COST MODELS.

. . . THE LACK OF OBJECTIVE, VERIFIABLE COST ESTIMATION MODELS MAKES IT DIFFICULT TO DETERMINE WHICH TECHNOLOGIES ARE WORTH PURSUING OR WHICH SHOULD BE DISCARDED. CREDIBLE, OBJECTIVE OPERATIONS COST METHODS-SIMILAR TO THOSE OF THE AIRLINE AND OTHER COMMERCIAL INDUSTRIES-SHOULD BE DEVELOPED, WHICH WOULD ALLOW THE GOVERNMENT TO ESTIMATE THE TOTAL COST OF INCORPORATING A NEW TECHNOLOGY OR MANAGEMENT PRACTICE AND THE SAVINGS IT COULD GENERATE. CURRENT MODELS HAVE PROVEN INADEQUATE, IN PART BECAUSE DATA ON PREVIOUS LAUNCH OPERATIONS EXPERIENCE HAVE NEITHER BEEN COLLECTED IN AN ORGANIZED WAY NOR PROPERLY MAINTAINED. WITHOUT ADEQUATE HISTORICAL DATA TO USE AS A BENCHMARK, COST ESTIMATION INVOLVES TOO MUCH GUESSWORK. CONGRESS MAY WISH TO DIRECT NASA AND DOD, OR SOME INDEPENDENT AGENCY, TO COLLECT THE NECESSARY HISTORICAL DATA AND TO DEVELOP BETTER COST ESTIMATING METHODS FOR SPACE TRANSPORTATION SYSTEMS."

U. S. Congress, Office of Technology Assessment, John Gibbons, Director, *Reducing Launch Operations Cost: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

One area of key importance in the operations integration effort is operations cost. The Operations Integration Team was tasked with developing estimates of relative operations cost. As noted in the OTA report quotation above, operations cost has not received a great deal of detailed analysis to date within the space transportation community. The Operations Cost Model (OCM) was used in this activity to addresses this topic, including both launch and flight operations.

OCM provides a traceable basis of estimate for operations cost, using existing vehicle cost data as the point-of-departure from which costs are estimated for a subject system. The primary focus is on identifying the way in which operations costs change as the level of flight rate activity varies. Model emphasis lies in capturing the cost of the full range of products and services required to operate a transportation system, as opposed to delving deeply into specific selected areas of operations. As such, it is intended for use primarily on advanced concept studies, in the absence of a detailed definition of all of a system's operations. It is not intended or represented as a replacement for a more rigorous, but time consuming definition and estimate of operational requirements.

OCM consists of two EXCEL spreadsheet models, the Conceptual Operations Manpower Estimating Tool (COMET) and OCM. The two models taken together form the overall OCM structure. COMET estimates the manpower required to perform the Flight Planning and Vehicle Processing activities for flight and launch operations respectively, based on user-defined vehicle and mission concepts. The resulting manpower estimates become inputs to the OCM spreadsheet, which fills out the balance of the launch and flight operations resource requirements to develop a complete operations cost estimate. This relationship is illustrated in Figure 1-1.

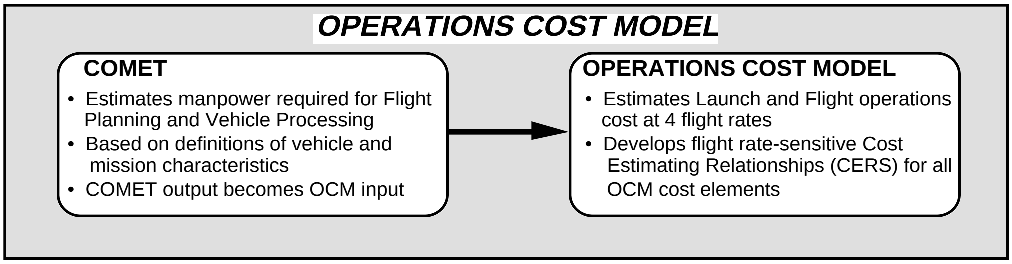


Figure 1-1 COMET to OCM Interrelationship

1.1 BACKGROUND

Operations costs are the largest contributor to architecture life cycle cost, however the operational definition for advanced concepts is usually limited, and does not include resource requirements for all functions necessary for operation of the vehicle, particularly those usually termed support or indirect. OCM was developed to provide a more thorough understanding of the nature and content of operations cost elements, thus providing "better" cost estimates.

OCM generates operations cost estimates for advanced concepts which provide a visible, traceable basis of estimate, using existing systems as a point-of-departure. OCM includes provisions for estimating the impacts of new ways of doing business on specific operations products and services. The output is easily auditable so that the estimate trace from existing systems was readily discernible. OCM provides flight rate-sensitive CER’s for use in architecture cost analysis.

COMET, a preprocessor for OCM, uses user-provided inputs regarding the nature of the vehicle and its mission to estimate manpower requirements for the two primary OCM elements, Vehicle Processing (Launch Operations) and Flight Planning (Flight Operations).

1.2 APPROACH

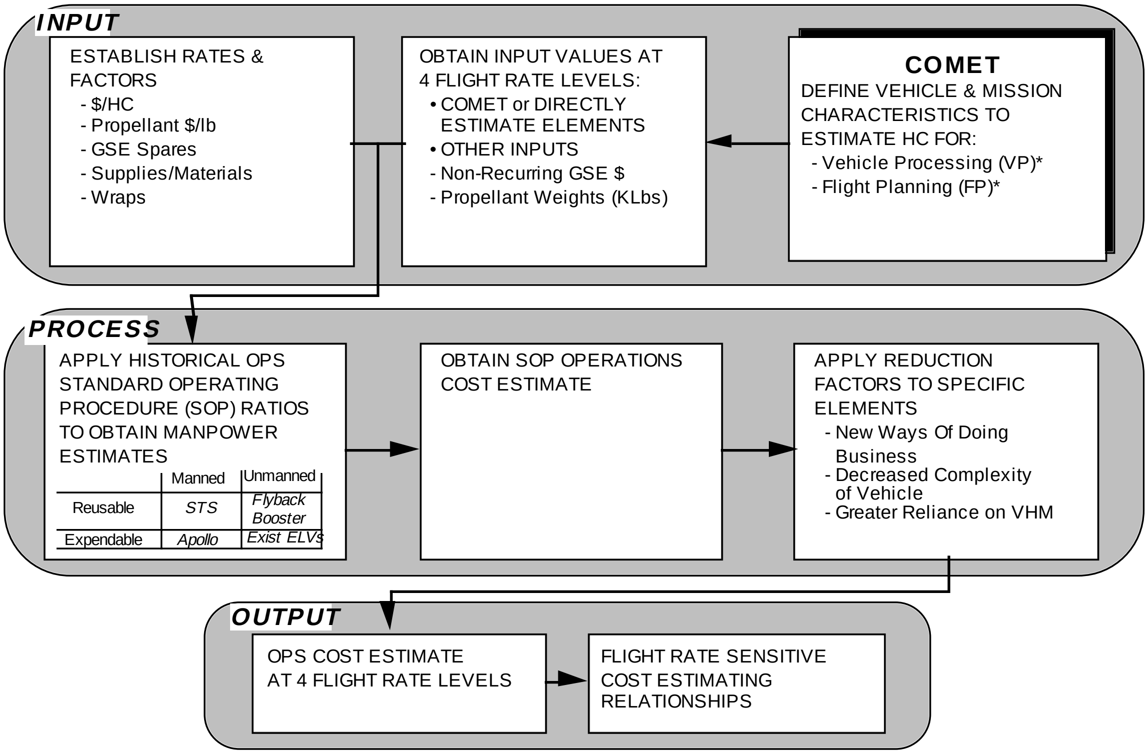
The underlying philosophical basis upon which OCM is founded is taken from an analytical process known as ratio analysis. Ratio analysis is widely used in the general financial community to evaluate the relative status and financial health of companies and individuals. It focuses on the relative relationship between sets of given cost elements. For example, the financial condition of companies is often evaluated based on the relationships of key financial statement account balances such as debt to equity and inventory to total assets on the balance sheet, and gross margins (cost of goods sold to gross revenue) on the income statement. Most individuals undergo a form of ratio analysis when applying for a loan, such as the principle, interest, tax, and insurance (PITI) index commonly used by mortgage companies to determine an individual's eligibility for a home loan.

The fundamental assumption upon which ratio analysis turns is that, although the absolute level of resources may vary, the relative relationship between the elements will remain approximately constant. The assumption holds only for like entities. For example, it is expected that oil companies will have comparable sets of ratios, as will retail grocery companies, but oil and grocery company ratios will not be comparable. Additionally, the assumption is valid only if the operating environment and processes, or culture, is approximately the same. A single mom-and-pop grocery store would not be expected to have the same ratios as a national chain.

OCM applies this approach to operations cost estimating. Using existing systems (Shuttle, Titan, Atlas, and Delta) as a basis, the relative resource requirements for operations products and services are defined for manned/reusable and unmanned/expendable systems. From these data points, manned/expendable and unmanned/reusable requirements are extrapolated. By its nature, operations are carried out with a relatively fixed level of manpower, who have the capacity to operate over a range of flights. The marginal change in resources given temporary changes in flight rate are typically fairly small. In order to most accurately reflect this, the OCM units of measure are manpower or employees (in the model, we will use the term headcount-HC to denote this). In addition, because of the large fixed base, cost per flight becomes a result, not an input. Total resources for given flight rates are estimated and divided by flight rate, rather than estimating resources per flight and multiplying by flights per year to obtain total resources.

The logic flow followed by OCM to generate a cost estimate is shown in Figure 1-2 which breaks the process into sections summarizing the inputs required, the method by which the inputs are manipulated, and the outputs.

Through the use of COMET and/or direct estimates from sources outside OCM, input values of Headcount per year (HC) are estimated at four flight rate levels for at least one element each within Flight and Launch Operations. When COMET is used, the direct estimates are of Vehicle Processing (Launch Operations) and Flight Planning (Flight Operations). In addition, inputs of cost per man-year and other rates and factors are entered. Finally, the type of vehicle is entered in terms of one of four possible rating sets: manned/reusable, unmanned/reusable, manned/expendable, or unmanned/ expendable. The type of vehicle, particularly the reusable/ expendable designation, is used as a gross surrogate definition for several second-tier operational complexity questions, such as reusable TPS system, crossrange/alternate landing sites, flight certification requirements, on-orbit payload operations, piloted versus crew-as-payload, and flight software size.



*units are Head Count (HC)

Figure 1-2 OCM Logic Flow

Based upon the inputs, OCM applies ratio percentages to estimate manpower requirements for all cost elements not directly estimated. There are four sets of ratios, one for each of the vehicle types described above. The manned/reusable and unmanned/expendable ratio sets reflect historical data for Shuttle and existing Expendable Launch Vehicle (ELV) operations. The other two sets are derived from Shuttle and ELV data, using analytical judgments as to the relative contributions of man rating and reusability to the magnitude of the difference in manpower requirements between the Shuttle and ELV data. All four ratio sets assume Standard Operating Procedures (SOP) for current launch vehicles.

The cost factor inputs transform the manpower estimates for each of the four flight rates to a cost estimate. At this point, cost adjustment factors to recognize such things as New Ways of Doing Business (NWODB) may be introduced. NWODB examples could be new technologies, new organizational management techniques, etc.

OCM output includes point estimates for all elements at each of the four input flight rates and, based on best-fit regressions, two flight rate-sensitive CER's for each OCM element, one each in linear and logarithmic forms.

COMET is the preprocessor spreadsheet which estimates manpower for the base OCM elements in each of two operations categories, Vehicle Processing (Launch Operations) and Flight Planning (Flight Operations). Each element is estimated at four flight rates. The approach utilized for COMET is illustrated in Figure 1-3.

COMET is based on historical data for existing systems as well as analyses done on TSA and previously as part of other advanced concept studies. The historical data is allocated to various vehicle characteristics such as reusability, manned, number and type of events in the mission profile, etc. Calibration points are calculated for Shuttle and ELV's at a rate of eight flights per year to provide an anchor for the estimate. Additionally, the characteristics of the relationships representing manpower as a function of flight rate are based on analysis of the historical data combined with analysts' judgment.

The user defines the vehicle being analyzed through answers to a series of interview questions. The collection of answers creates a vehicle and mission definition against which the allocated database is matched to build manpower estimates for Vehicle Processing and Flight Planning. Taken together, the answers provide the basis for a manpower estimate at eight flights per year. With this point estimate and the flight rate sensitivity relationship derived previously from historical data, the output can be generated. COMET outputs are the manpower estimates for each element at four user-defined flight rates as well as the flight rate vs. manpower coefficients. This output is linked directly to OCM as an input to generate a complete operations manpower cost estimate.

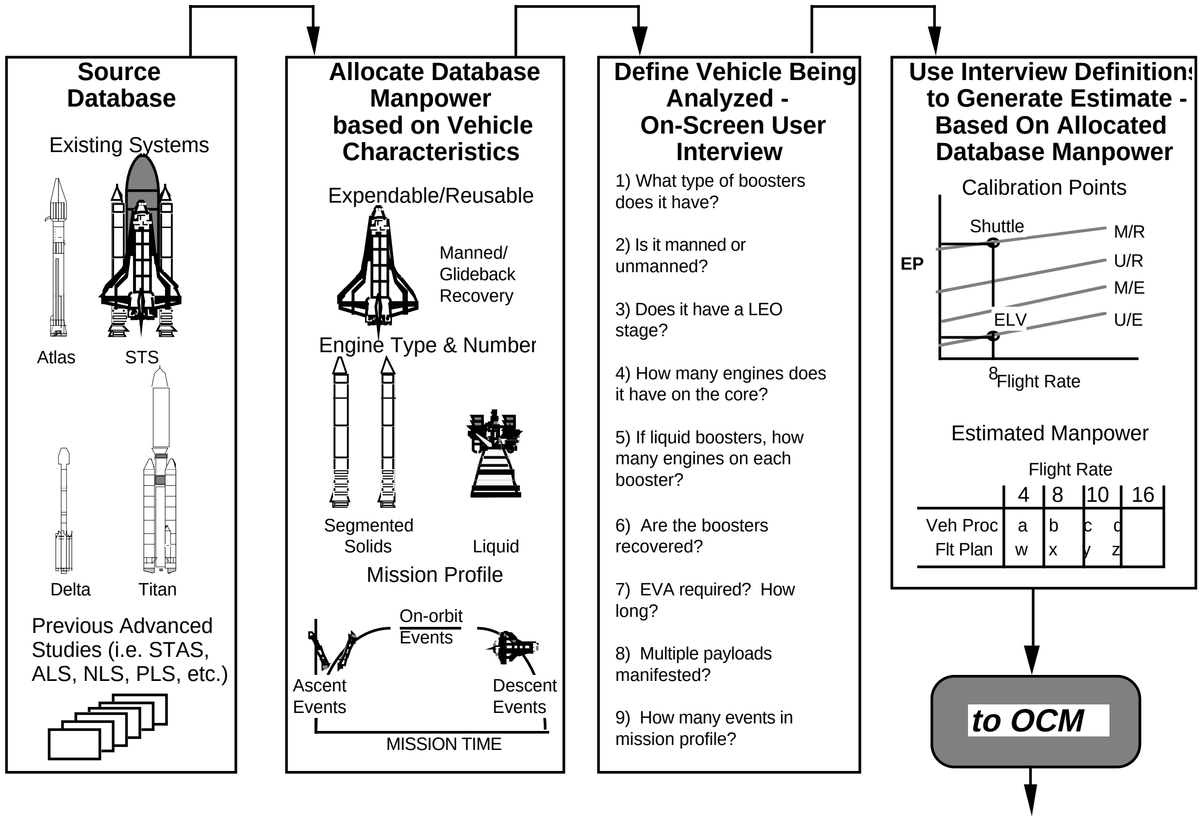


Figure 1-3 COMET Approach

OCM is organized in a schematic, shown in Figure 1-4, of the cost elements and their relationship within the overall operations structure defined for the model. Vehicle operations is divided into two primary categories, Launch Operations and Flight Operations. Within these categories are the OCM cost elements. Element definitions are provided on the following pages. The acronym list in the front of the User's/Analyst's Guide will be a helpful reference for understanding the schematic.

The schematic uses Shuttle operations organization as a point-of-departure, with existing ELV operations data fitted to the structure within the appropriate elements. Vehicle hardware elements, such as expendable hardware production and reusable hardware spares, are excluded as part of this model.

Some costs are estimated as factors of the OCM elements, including miscellaneous supplies and materials associated with each element, and costs generally referred to as "Wraps", defined as contractor fee, government support (e.g. NASA R & PM), and any contingency the analyst may choose to add.

The Launch Operations portion of OCM contains 8 cost elements which capture the primary products and services necessary for a launch vehicle launch as defined in Table 1-1. Not all elements apply to all vehicles (e.g. L3 Recovery Operations would not apply to expendable vehicles). Each element has a corresponding trace to Shuttle and existing ELV cost elements which can be found in Appendix 2 of this Guide. Vehicle Processing is the base Launch Operations element which is estimated by COMET.

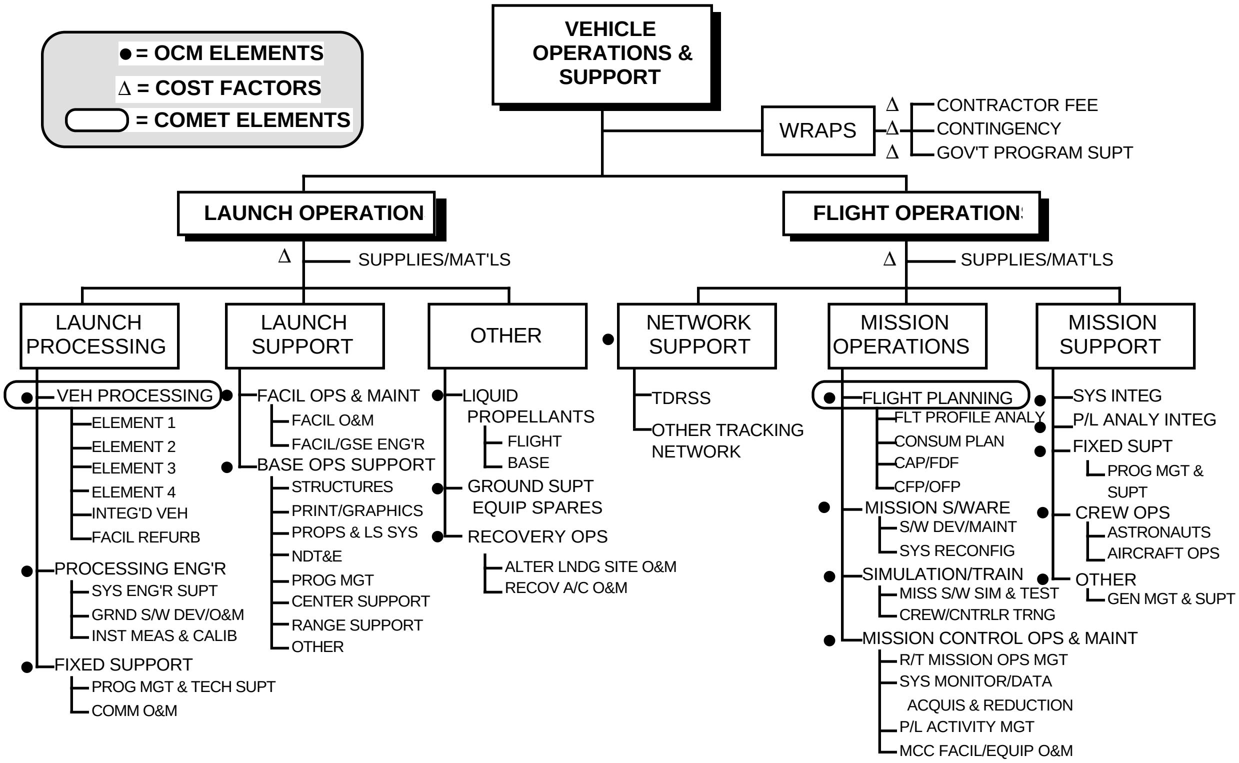


Figure 1-4 OCM Schematic

The Flight Operations portion of OCM contains 10 cost elements which capture the primary products and services necessary for a launch vehicle flight as defined in Table 1-2. As with Launch Operations, not all elements apply to all vehicles (e.g. F7 Crew Operations would not apply to unmanned vehicles). The Flight Planning cost element is the base element which is estimated by COMET.

Table 1-1 Launch Operations Element Definitions

	OCM COST ELEMENT	DEFINITION	PRIMARY PRODUCTS & SERVICES
L1	VEHICLE PROCESSING	Hands-on vehicle processing of all vehicle elements, including individual element receiving, inspection, flight preparation, integration of all elements, cargo to vehicle integration, countdown and launch operations, and reusable element refurbishment	Checkout, integration, launch, and refurbishment of all vehicle elements.
L2	PROCESSING ENGINEERING	Engineering support to ground processing, including configuration control, test engineering, and operations and maintenance of ground software and computer hardware.	Engineering support services, O&M of all ground software systems
L3	RECOVERY OPERATIONS	All activities associated with the recovery of reusable flight hardware, including recovery operations and return to refurbishment site.	Reusable vehicle recovery and transport to processing site.
L4	FIXED SUPPORT	General administration and support activities such as general management, business management and support (finance, human resources, contracts, etc.), SRQA, logistics management, training, comm systems O&M, etc.	Program mgt & support, technical support services (safety, communications, training, etc.)
L5	FACILITY OPS & MAINT	Operations and maintenance of launch facilities and ground support and real property installed equipment, includes preventive and corrective maintenance, resource scheduling, and facility modifications.	Operation, maintenance, and modification of launch facilties
L6	BASE SUPPORT	General support for launch site operations, including generic facility and resource maintenance (ie. roads & grounds, railroads, multi-use test and storage facilities), base security, fire and medical, range support, etc.	Generic launch site support services applicable to multiple site users.
L7	PROPELLANTS	Procurement and storage of all liquid propellants and gases, including flight propellants, boiloff replacements, and purge gases	Liquid propellants and gases necessary for flight and ground ops
L8	GSE SPARES	Replenishment of ground support equipment (GSE) stock of spares, does not include initial non-recurring spares lay-in	Stock of GSE spare parts

Table 1-2 Flight Operations Element Definitions

	OCM COST ELEMENT	DEFINITION	PRIMARY PRODUCTS & SERVICES
F1	FLIGHT PLANNING	Activities associated with design and analysis leading to development of operational flight profile, including such things as ascent/on-orbit/descent, cargo operations, and crew activities. Support to associated functions such as software, training and systems integration. Analyses include such things as trajectory and abort analyses, Inititialization (I) load development, propulsive and non-propulsive consumables planning, and flight/crew activities plans.	Flight profile groundrules and data provided to flight and ground software for coding/reconfiguration; data support to flight controller and crew training
F2	MISSION SOFTWARE	Flight and associated ground mission software coding and certification, computer hardware/software maintenance	Flight-certified software, software configuration control, software tool development and maintenance
F3	SIMULATION & TRAINING	Support to and conduct of mission operations simulations and training for flight software, crew and flight controllers. Maintenance of simulation equipment and facilities.	Mission simulations for all mission operations, including flight software, crew activities, cargo ops
F4	MISSION CONTROL O & M	Real-time mission control and flight management operations, MCC facility and equipment O & M	Manning of flight control consoles and equipment during flight, maintenance of equip and facilities
F5	SYSTEMS INTEGRATION	Systems engineering support and control, including system configuration control and maintenance, engineering changes control and implementation, support to flight design analyses, system requirements development and maintenance, management support of systems engineering efforts.	Program configuration control, system engineering changes implementation and verification, information management, business management.
F6	PAYLOAD ANALYTICAL INTEG	Payload/cargo interface analyses, develop and maintain payload Interface Control Documents	Vehicle manifests, payload ICDs, supporting documentation control
F7	CREW OPERATIONS	Astronaut office and support, trainer aircraft operations & maintenance	Flight crews, crew trainer aircraft O & M
F8	FIXED SUPPORT	Supporting engineering and administrative services, such as flight operations program management, subsystems engineering support, miscellaneous center support	Support engineering, miscellaneous administrative support functions (such as TV services)
F9	OTHER	General management and support	Overall program management and support services such as general management and outside support (auditing, etc.)
F10	NETWORK SUPPORT	Ground-vehicle links, provides tracking, telemetry, command, data acquisition, communications, and data processing support	Ground-vehicle communications links

1.3 LAUNCH VEHICLES AND AIRCRAFT LIKE OPERATIONS

Often times the launch vehicle world has looked with envy at the relative operational simplicity found in the aircraft world and sought to draw an appropriate analogy. The phrase "do it like an airplane" has often led to large projected reductions in operations manpower, processing time and other operations factors resulting in a significantly lower cost. There are some lessons to be learned from the aircraft world that can be applied to launch vehicle operations, but one must fully understand the implications and differences between airplanes and rockets before expecting a magical reduction due to "doing it like an aircraft".

A major reason why this aircraft operability dividend may not be realistic is the difference in operating environments. Although the mission of taking off, performing a mission, and returning to Earth may make the difference between a Space Shuttle and an airplane appear transparent, this similarity is misleading. The high performance demands of entering, performing in, and exiting the space environment has driven space launch vehicle designers to stress higher performance over any other characteristic. This leads to significant differences in design margin and the resultant testing that is required. Table 1-3 illustrates the difference in design factors commonly found between aircraft and launch vehicles.

As the table illustrates, launch vehicles are pushing performance boundaries on most of their major subsystems. This means that a minor miscalculation of thrust produced, component weights, structural loads or any other vehicle characteristics can result in a reduction of payload capability to zero, or worse lead to a mission loss. This forces designers to extract the maximum performance from every subsystem. As a result, programs are often fraught with technical and cost risks resulting from subsystems falling short of program requirements. Also, to insure that the system will meet peak performance every flight, extensive testing and inspection is required, which in turns drives up operations cost. Finally, reliability suffers because everything is at the edge of performance margins. Because the costs associated with failures are quite high, the lowered reliability has a lasting cost effect on the system.

To make the space vehicle/aircraft analogy completely credible would take a radical change in design philosophy, which can then make the vehicle unfeasible in cost and/or technical capability. Most aircraft are designed with very high reliability against total mission failure or mission loss.

Table 1-3 Aircraft to Launch Vehicle Comparison

Characteristics	Aircraft	STS (Orbiter)	ELVs
Structures:			
Factors of Safety	1.5	1.4	1.25
GLOW (Klbs)	618	4,426	1,888
Design Life (Missions)	8,560	100	1
Propulsion:			
Thrust (Vac, Klbs)	30 to 60	470	200 to 17,500
Thrust/Weight Ratio	4.5	74	60 to 140
Operating Temp (°F)	2,550	6,000	500 to 5,000
Operating Press (PSI)	140	2,970	500 to 1,200
Cruise Power Level	25%	109%	100%
Mechanical:			
Specific Horsepower	2	108	3 to18
RPM	13,450	35,014	5,000 to 34000

** taken from "Operational Design Factors for Advanced Space Transportation Vehicles", Whitehair, et al, IAF-92-0879*

This is accomplished through large design margins in all subsystems, redundancy, or some combination of the two. In the launch vehicle world this can translate into large increases in weight and reduced payload, a generally unacceptable condition. Current rocket technology does not provide much room for design margins, making incorporation of the large design and operational margins characteristics of aircraft extremely difficult.

Another area where aircraft and launch vehicles vary, especially in terms of operations cost, is the large production runs and large number of vehicles in operation. High rates allow aircraft to take full advantage of economies of scale by spreading costs over a large base and providing increasing confidence in each operation. Even the most ambitious mission models for launch traffic into the next century pale in comparison with most nominal aircraft mission requirements, both military and commercial.

The problems described above notwithstanding, there are many things the launch vehicle business can learn from its aircraft counterparts. Certain logistics, maintenance, task scheduling, and other activities could make launch operations more efficient and cost effective. The OTA "Reducing Launch Operations Cost" report cited earlier outlined the following airline practices which could be applied to space transportation:

- involve operations personnel in design changes;
- stand down to trace and repair failures only when the evidence points to a generic failure of consequence;
- design for fault tolerance;
- design for maintainability;
- encourage competitive pricing;
- maintain strong training programs;
- use automatic built-in checkout of subsystems between flights; and

- develop detailed operations cost estimation models.

Of these recommendations, the last is that which COMET/OCM is attempting to address. Some preliminary areas identified within COMET/OCM where aircraft style operations can have an impact have been identified in Table 1-4.

Table 1-4 OCM/COMET Potential Aircraft Style Impacts

OCM	ELEMENT NAME	EXAMPLE IMPACTS
L1	Vehicle Processing	Operability design (LRUs, BIT, LIPs, etc.) to reduce maintenance, testing, inspection, integration
L2	Processing Engineering	Paperless documentation systems, automated ground tests, less system complexity to increase efficiency, reduce sustaining engineering support
L3	Recovery Ops	High return to site probability (crossrange, accuracy, all-weather robustness) to reduce/eliminate recovery transportation
L8	GSE Spares	Reduce amount of GSE, but increase overall spares inventory (higher POS)
F1	Flight Planning	Standardize mission profiles, increase performance margins to reduce dependency on detailed flight planning and analysis
F2	Mission Software	Robust code (automated guidance and navigation, easy P3I evolution of new technology, etc.), increase margins to reduce software complexity, changes/reconfigurations and certification
F5	System Integration	Simplified, robust, high margin system to reduce support engineering and integration
F6	P/L Analytical Integration	Standard interfaces/containerized cargo, increased margins to reduce payload analysis and integration
F8	Fixed Support	Simplified system, higher flight rate, centralized management to reduce sustaining engineering and increase amortization base

1.4 HRST CONCEPT ANALYSIS WITH COMET/OCM

THE COMET/OCM analysis of HRST concepts included facilities costs which were developed on a separate Excel spreadsheet. Facilities costs included Construction of Facilities (CofF) costs based on volume of the facility or facilities required, the Ground Support Equipment (GSE) associated with the type of facility and cost of initial spares for the facility. The costs were based on similar facilities at the current launch site at Kennedy Space Center (KSC) with provisions for cost reductions due to modernization.

It was assumed that a suite of facilities required for each “family” of concepts, such as HTHL, VTVL and VTHL types and whether two or single stage. The list of facilities in shown in Table 1-5. The facilities were further broken out as to whether they would be furnished by the Government or by the commercial Space Port developer, as indicated in the table. These costs were then used by the Cost Integration team in developing Life cycle costs and as input into OSAMS. The facilities were sized for costing purposes by the conceptual vehicle footprints (length, width, height as provided by the concept developers) again basing the facility size on the existing KSC facilities currently used for similar processing functions as the concept. The number of facilities required was assumed to be the same for each concept rather than determining a flight rate for each concept and thereby a different number of bays within a facility or different number of facilities for different concepts. The Baseline flight rate for facilitization was assumed to be 50 flights per year.

As indicated above COMET estimates manpower requirements for launch and flight operations based on vehicle characteristic and mission profile data provided by the user. Tables 1-6 and 1-7 show the Mission Profiles and Vehicle Characterization Data input into COMET to develop headcount estimates for flight and launch operations. OCM utilizes the COMET headcount output to develop operations costs for 4 flight rates. OCM allows the user to adjust the COMET results with the factors discussed above and as shown in Table 1-8. The baseline adjustment factors were further modified by introducing adjustments based on TSP and Engine Processing complexity factors as shown in Tables 1-9 and 1-10. The final reduction factors used in OCM are shown at Table 1-11, which the reader should bear in mind are the percentages by which the required headcounts are reduced from STS levels.

Table 1-5 Concept Facilities Costs

FACILITIES	TO BE PROVIDED BY	0-ATS BCS	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL TSTO Rocket w/LA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)	9 - HTHL SSTO w.MHD (Anser/Chase)
Launch Assist	GOVT			150	150	150						
At-Grade Guideway												
Tunnel												
Elevated Guideway												
Guideway Electrical System												
Communication& Control System												
Payload/Cargo Processing Facilities	COMM	109	109	109	109	109	109	109	109	109	109	109
Traffic/Flight Control Facilities	GOVT	1027	1027	1027	1027	1027	1027	1027	1027	1027	1027	1027
Launch Facilities	GOVT	121	121				121	121		121		
Landing/Recovery Facilities	GOVT	50	6.69	50	50	50	50	50	50	50	50	50
Vehicle Turnaround Facilities	COMM	769	996	735	648	812	665	601	770	912	741	935
Booster Processing Facility	COMM			0								
Vehicle Assembly/Integration Facilities	COMM			0						301		
Vehicle Depot Maintenance Facilities	COMM	56.3	95	52	46.4	57.6	50.1	46	55.9	36.8	20.7	25
Spaceport Support Infrastructure Facilities	GOVT											
Concept-Unique Logistics Facilities	COMM	21.5	30	20.4	18.3	22.4	19	17.4	21.5	37.3	53.5	65
Transportation System Ops Planning and Mgt Facilities	GOVT	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29
Expendable Element Faciities	COMM											
Community Infrastructure	GOVT											
TOTAL COMM FACILITIES COST		955	1230	917	822	1001	843	773	956	1396	924	1134
TOTAL GOV'T FACILITIES COST		1227	1184	1256	1256	1256	1227	1227	1106	1227	1106	1106
TOTAL FACILITIES COST		2182	2413	2173	2078	2258	2070	2000	2063	2623	2030	2241

For the purposes of COMET/OCM operations cost analysis, based on the RMAT results indicating that TPS and Main Propulsion System (MPS) processing were the maintenance burden drivers, it was decided to further adjust the reduction factors for those subsystems, normalizing concept TPS and Engine complexity to the STS. Assuming that TPS and MPS processing are each 30% of the Vehicle Processing, Processing Engineering and Systems Integration burdens (Table 1-8), the equation below was used to apply TPS and MPS reductions to the baseline reduction factor:

Reduction Percentage = Baseline HC Reduction Factor / (.3*TPS Adjustment Factor+.3*MPS Adjustment Factor+.4)

It must be stressed that the TPS and Engine Processing Adjustment Factors are not an attempt to increase the accuracy of the COMET/OCM but rather to highlight and emphasize relative differences among the concepts in areas related to operations. For sub-system adjustment factors greater than 1 (more complex), the reduction factor is decreased. For adjustment factors less than 1, the reduction is increased. The TPS Processing Adjustment Factors are shown in Table 1-9 and the Engine Processing Adjustment Factors in Table 1-10. The resulting headcount reduction factors are shown in Table 1-11. The headcounts for each concept are then reduced from the basic COMET estimation by the percentages shown, producing the final headcounts and operations cost shown in Figure 1-4.

Table 1-6 Concept Flight Event Profiles

	CONCEPTS	Shuttle	BCS=ATS SSTO All Rocket-Biprop	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL SSTO All Rocket wLA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)	9 - HTHL SSTO w.MHD (Anser/Chase)
EVENTS													
Ascent Maneuvers/Events													
1	Launch assist initiation				1	1	1						
2	Main Rocket Engine Start	1	1		1	1	1	1	1	1	1	1	1
3	Main Scram/Ram jet engine start											1	1
4	Booster Engine Start	1											
5	Separation from Launch assist				1	1	1						
6	Liftoff	1	1	1	1	1	1	1	1	1	1	1	1
7	Launch assist shutdown				1	1	1						
8	Booster engine burnout/cut-off	1											
9	Pull over to horizontal		1	1				1	1		1		
10	Booster engine separation	1											
11	Main Scram/Ram jet engine start			1		1	1			1			
12	Main Rocket engine cut-off	1	1	1		1	1	1	1	1	1	1	1
13	Ram/Scram mode change			2		1	1			1		3	2
14	Pull up to vertical			1	1	1	1			1		1	1
15	Inlet configuration change			1									
16	Main Rocket engine start			1		1	1			1		1	1
17	Main Scram/Ram jet engine cut-off			1		1	1			1		1	1
18	Main Rocket engine cut-off			1	1	1	1			1		1	1
19	ET separation	1											
20	P/A Module separation												
21	2nd + stage engine ignition										1		
22	1st stage attitude alignment										1		
23	1st stage Final approach landing alignment										1		
24	1st stage runway landing										1		
25	2nd + stage engine cut-off										1		
26	2nd + stage separation/ET separation												
27	OMS Ignition	1	1	1	1	1	1	1	1	1	1	1	1
28	OMS cut-off	1	1	1	1	1	1	1	1	1	1	1	1
29	Insulation panel jettison												
30	Payload fairing jettison												
31	Alignment to S/C Separation attitude	1	1	1	1	1	1	1	1	1	1	1	1
32	Spacecraft separation	1	1	1	1	1	1	1	1	1	1	1	1
33	Upper stage collision avoidance maneuver												
34	Booster or P/A Module parachute deploy												
	TOTAL ASCENT EVENTS	**11**	**8**	**15**	**11**	**16**	**16**	**8**	**8**	**13**	**13**	**15**	**14**
On-Orbit Maneuvers/Events													
1	Orbit change OMS/RCS ignition	1	1	1	1	1	1	1	1	1	1	1	1
2	Orbit change OMS/RCS cut-off	1	1	1	1	1	1	1	1	1	1	1	1
3	Alignment to S/C separation attitude												
4	EVA attitude adjustments												
5	Spacecraft separation												
6	Rendevous with docking platform												
7	Docking maneuver												
8	Spearation from docking platform												
	TOTAL ON-ORBIT EVENTS	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Descent Manevers/Events													
1	Deorbit OMS/RCS ignition	1	1	1	1	1	1	1	1	1	1	1	1
2	Deorbit OMS/RCS cutoff	1	1	1	1	1	1	1	1	1	1	1	1
3	Pre re-entry attitude alignment	1	1	1	1	1	1	1	1	1	1	1	1
4	Post re-entry attitude alignment												
5	Deploy turbofan			1									
6	Inlet configuration change			1									
7	Main Ram/Scram/Loiter engine start			1						1			
8	Parachute deployment												
9	Pull up to vertical			1									
10	Final approach landing alignment	1	1	1	1	1	1	1	1	1	1	1	1
11	Runway/verticle landing	1	1	1	1	1	1	1	1	1	1	1	1
12	Main Ram/Scram engine cut-off			1						1			
13	Splashdown												
14	Flotation device deployment												
	TOTAL DESCENT EVENTS	**5**	**5**	**10**	**5**	**5**	**5**	**5**	**5**	**7**	**5**	**5**	**5**

Table 1-7 Concept Vehicle Characterization

	INTERVIEW QUESTIONAIRE					CONCEPTS	BCS=ATS SSTO All Rocket-Biprop	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL TSTO All Rocket wLA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)	9 - HTHL SSTO w.MHD (Anser/Chase)
	NOTE : For illustrative purposes, blocks are only checked only as required to illuminate all interview questions																
		Interview-1															
		General Information															
1)	Vehicle Name:	**Concept Name**															
2)	Processing Concept:	**Integrate-Transfer-Launch (ITL)**	x		**FOR ALL CONCEPTS**		x	x	x	x	x	x	x	x	x	x	x
		Build-On-Pad (BOP)															
		N/A															
3)	Primary launch site	**KSC (for all Concepts)**					KSC	KSC	KSC	KSC	KSC	KSC	KSC	KSC	KSC	KSC	KSC
4)	Enter 4 flight rates	**#1:**	50		**FOR ALL CONCEPTS**		50	50	50	50	50	50	50	50	50	50	50
		#2:	100		**FOR ALL CONCEPTS**		100	100	100	100	100	100	100	100	100	100	100
		#3:	150		**FOR ALL CONCEPTS**		150	150	150	150	150	150	150	150	150	150	150
		#4:	200		**FOR ALL CONCEPTS**		200	200	200	200	200	200	200	200	200	200	200
		Interview-2															
		Core Description (Used as 1st Stage or Launch Assist)															
	Core Definition																
1)	Is there a Core Stage or Launch assist:	**Yes:**		x	**No:**		No	No	Yes	Yes	Yes	No	No	No	Yes	No	No
2)	Enter the # of engines or solids:		Data		**"CONCEPTS WTS&DIMEN"**				1	1	1				6		
3)	Enter the type of core:	**Solid:**		x													
		Hybrid:															
		Liquid:		x					x	x	x				x		
	a. What type of Solid/Hybrid is it:	**Monolithic (M):**			**Segmented (S):**												
	b. Is there a Recoverable P/A module?	**Yes:**		x	**No:**				Yes	Yes	Yes				Yes		
	c. Enter Recovery type:	**Parachute/Water:**															
		Parachute/Land:															
		Flyback/Land:							x	x	x				x		
		Interview-3															
		Booster Description															
	Booster Definition																
1)	Does this vehicle have Boosters:	**Yes:**		x	**No:**		No	No	No	No	No	No	No	No	No	No	No
2)	Enter the number of boosters:		Data		**"CONCEPTS WTS&DIMEN"**												
3)	Enter the type of boosters:	**Solid:**		x													
		Hybrid:															
		Liquid:		x													
	a. What type of solid/hybrid are they:	**Monolithic (M):**			**Segmented (S):**	x											
	b. Enter the number of engines per booster:		Data		**"CONCEPTS WTS&DIMEN"**												
4)	Are the boosters reusable:	**Expendable:**			**Reusable:**	x											
	a. Enter recovery type:	**Parachute/Water:**															
		Parachute/Land:															
		Flyback/Land:															
		Interview-4															
		Upper Stage(s) Description															
	Upper Stage(s) Definition																
1)	Enter the number of Upper Stages:		2				1	1	1	1	1	1	1	1	1	1	1
2)	**1st Upper Stage:**																
	a. Enter propulsion type:	**Solid:**															
		Hybrid:															
		Liquid:		X			X	X	X	X	X	X	X	X	X	X	X
	b. Enter the number of engines:		1		**FOR ALL CONCEPTS**		1	1	1	1	1	1	1	1	1	1	1
	c. Are CTV/OMV functions performed:	**Yes:**			**No:**		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	d. Reusable or Expendable:	**Expendable:**			**Reusable:**		Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp
3)	**2nd Upper Stage:**																
	a. Enter propulsion type:	**Solid:**															
		Hybrid:															
		Liquid:		x													
	b. Enter the number of engines:																
	c. Are CTV/OMV functions performed:	**Yes:**		x	**No:**	x											
	d. Reusable or Expendable:	**Expendable:**		x	**Reusable:**	x											
		Interview-5															
		LEO Stage Description															
	LEO Stage Definition:																
1)	Is there a LEO Stage:	**Yes:**		x	**No:**		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2)	Does the LEO stage return:	**Yes:**		x	**No:**		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	a. Enter Return Method:	**Parachute/Water:**															
		Parachute/Land:															
		Flyback/Land:		x			X	X	x	x	x	x	x	x	x	x	x
	b. Is this LEO Stage Reusable or Expendable?	**Reusable:**		x	**Expendable:**		Reuse	Reuse	Reuse	Reuse	Reuse	Reuse	Reuse	Reuse	Reuse	Reuse	Reuse
3)	Is this LEO Stage Manned or Unmanned?	**Manned (M):**			**Unmanned (U):**	X	U	U	U	U	U	U	U	U	U	U	U
4)	Is there a main propulsion system (MPS)?	**Yes:**		x	**No:**		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	a. How many engines:		Data		**"CONCEPTS WTS&DIMEN"**		7	12	4	2	8	7	7	5	3	4	1
5)	The Orbiter has approx 27,500 Tiles & Blankets for reusable TPS.																
	What fraction of this, if any, does the LEO Stage have:		Data		**"OPS BASELINE FACTORS"**		109%	73%	86%	30%	194%	93%	83%	35%	71%	268%	0%

Table 1-7 Concept Vehicle Characterization (Continued)

INTERVIEW QUESTIONAIRE (CONTINUED)					CONCEPTS	BCS=ATS SSTO All Rocket-Biprop	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL TSTO All Rocket wLA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)	9 - HTHL SSTO w.MHD (Anser/Chase)
Interview-6																
Cargo Integration Description																
Cargo Integration																
Is there Payload other than Man:		**Yes:**	x	**No:**	x	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
What integration method is used:		**Off-Line Encaps:**	x	**ALL CONCEPTS**		x	x	x	x	x	x	x	x	x	x	x
		Pad Encaps:														
		Payload Bay:														
Interview-7																
Cross Training (Manpower Sharing) Effects																
Booster / Core / Upper Stages / LEO Stage																
Booster Cross Training																
Manpower sharing between processing & stacking / integration:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce stacking by what percentage:		**NOT USED FOR HRST**														
Manpower sharing between the boosters & the core:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce booster manpower by what percentage:		**NOT USED FOR HRST**														
Core/Upper Stage/LEO Stage Cross Training																
Sharing between Upper Stage #1 processing & integration:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce Upper Stage-1 integration by what percentage:		**NOT USED FOR HRST**														
Sharing between Upper Stage #2 processing & integration:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce Upper Stage-2 integration by what percentage:		**NOT USED FOR HRST**														
Sharing between Upper Stage 1 & Core:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce Upper Stage 1 manpower by what percentage:		**NOT USED FOR HRST**														
Sharing between Upper Stage 2 & Core:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce Upper Stage 2 manpower by what percentage:		**NOT USED FOR HRST**														
Sharing between Upper Stage 1 & 2:		**Yes:**	x	**No:**	x	No	No	No	No	No	No	No	No	No	No	No
a. Reduce Upper Stage 2 manpower by what percentage:		**NOT USED FOR HRST**														
Sharing between LEO Stage processing & integration:		**Yes:**	X	**No:**	x	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
a. Reduce LEO Stage integration by what percentage:	100%	**ASSUMED FOR HRST CONCEPTS**				100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Integrated Vehicle / Payload Processing Cross Training																
Sharing for launch countdown:		**Yes:**	X	**No:**	x	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
a. Reduce integrated vehicle manpower by what percentage:	50%	**ASSUMED FOR HRST CONCEPTS**				50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Sharing between Payload processing & integration:		**Yes:**	X	**No:**		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
a. Reduce integration by what percentage:	50%	**ASSUMED FOR HRST CONCEPTS**				50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Interview-8																
Mission Description																
Mission Profile Design																
Enter # of Events during:	**Ascent:**		**"FLIGHT EVENTS"**			8	15	11	16	16	8	8	13	13	15	14
	On-Orbit:		**"FLIGHT EVENTS"**			2	2	2	2	2	2	2	2	2	2	2
	Descent:		**"FLIGHT EVENTS"**			5	10	5	5	5	5	5	7	5	5	5
Will most missions be standardized or mission peculiar?		**Standardized:**	x	**Peculiar:**	x	Stand	Stand	Stand	Stand	Stand	Stand	Stand	Stand	Stand	Stand	Stand
Will most payloads be mature spacecraft designs																
or will they primarily be first flights?		**Mature:**		**First Flight:**		Mature	Mature	Mature	Mature	Mature	Mature	Mature	Mature	Mature	Mature	Mature
Trajectory and post flight analysis is:		**Manual:**		**Automated:**		Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto
Crew Activity Planning																
Is this a manned vehicle?		**Yes:**		**No:**	X	No	No	No	No	No	No	No	No	No	No	No
	Data	**NOT USED IN HRST**														
	Data	**NOT USED IN HRST**														
			x		x											
Mission Model																
Enter the percent of missions that are:	**Commercial:**	78%	**SAME ALL CONCEPTS**			78%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
	Civil / NASA:	19%	**SAME ALL CONCEPTS**			19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
	DoD:	3%	**SAME ALL CONCEPTS**			3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%

Table 1-8 Baseline Headcount Adjustment Factors

	ATS	TSTO(R)	SSTO(R)LA	RBCC	RBCCwLA	
LAUNCH OPERATIONS						DESCRIPTION/BASIS
VEH PROC	40%	40%	45%	50%	45%	less m/pwr intense turnaround, no vertical intg (except TSTO)
PROC ENGR	10%	40%	45%	50%	45%	reliance on IVHM
RECOV OPS						
FIXED SUPT	0%	33%	33%	33%	33%	program approach
FACIL O & M	50%	40%	45%	50%	45%	Less facilities for SSTO than STS
BASE SUPT	50%	40%	45%	50%	45%	Less facilities for SSTO than STS
FLIGHT OPERATIONS						
FLT PLANNING	20%	20%	20%	20%	20%	adaptive gn&c, standard profiles
MISS S/WARE	-20%	-20%	-20%	-20%	-20%	Increase reliance/complexity of flight software
SIM/TRNG	30%	50%	50%	75%	75%	Less flight controller involvement, automated flight
MIS CTL O & M	30%	70%	70%	70%	70%	Automated systems requiring less reconfiguration
SYS INTEGR	40%	25%	45%	50%	45%	SSTO, relatively less systems to integrate than STS
P/L ANALY INT	30%	50%	50%	50%	50%	Primarily standarde missions, less payload to cargo analy
CREW OPS	75%	75%	75%	75%	75%	No crew, maintain SCA-like availability
FIXED SUPT	100%	100%	100%	100%	100%	Consolidate with launch site
OTHER	100%	100%	100%	100%	100%	Not apply

Table 1-9 TPS Processing Adjustment Factors

TPS Processing Adjustment Factors									
CONCEPT	TPS Subsystem (klbs)	TPS/Vehicle dry weight	% TPS Weight/STS	Reduction due to Technology Advances in TPS	Active Cooling (y/n)	Active Cooling Complexity Factor	Max Transition Mach #	Mach # Complexity Factor	% TPS Related to Processing HC Requirements
Shuttle	19000	0.1086	1.00	0.00	n	1.00	NA	1.00	**1.0000**
BCS=ATS SSTO All Rocket-Biprop	20760	0.1023	1.09	0.00	n	1.00	NA	1.00	**1.0926**
1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	13953	0.0869	0.73	0.50	y	1.15	12	1.10	**0.4645**
2 - HTHL SSTO All Rocket w/LA (Woodcock)	16332	0.1186	0.86	0.50	n	1.00	NA	1.00	**0.4298**
2a - HTHL SS w.LA SERJ (GT Argus 40)	5749	0.0619	0.30	0.50	n	1.00	6	1.05	**0.1589**
3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	36840	0.1997	1.94	0.50	y	1.15	20	1.20	**1.3379**
4 - BCS 92 w.Adv.Eng. (Rdyne)	17723	0.1119	0.93	0.50	n	1.00	NA	1.00	**0.4664**
5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	15858	0.1229	0.83	0.50	n	1.00	NA	1.00	**0.4173**
6 - HTHL SSTO ESJ (GT Hyperion)	6743	0.0589	0.35	0.50	y	1.15	10	1.10	**0.2245**
7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lepsch)	13448	0.0839	0.71	0.50	n	1.00	NA	1.00	**0.3539**
8 - HTHL SSTO w.LACE (LaRC/Petley)	50881	0.2121	2.68	0.50	y	1.15	24	1.20	**1.8478**
9 - HTHL SSTO w.MHD (Anser/Chase)	0	0.0000	0.00	0.50	y	1.15	15	1.10	**0.0000**

Table 1-10 Engine Processing Adjustment Factors

Engine Processing Adjustment Factors									
CONCEPT	OMS Integrated (y/n)	OMS Integration Factor	# Main Engines	Main Engine Integration Factor	# OMS Engines	#OMS Engine Integration Factor	Engine Complex- ity Factor	Launch Assist Processing	Launch Processing Complexity
Shuttle	n	1.0	3	1.0	2	1.00	1.0	1.00	**1.00**
BCS=ATS SSTO All Rocket-Biprop	n	1.0	7	1.1	2	1.00	1.1	1.00	**1.21**
1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	n	1.0	12	1.2	4	1.05	1.1	1.00	**1.39**
2 - HTHL SSTO All Rocket w/LA (Woodcock)	n	1.0	4	1.0	2	1.00	1.0	1.10	**1.10**
2a - HTHL SS w.LA SERJ (GT Argus 40)	n	1.0	2	0.9	2	1.00	1.1	1.10	**1.09**
3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	y	0.9	8	1.1	0	0.95	1.3	1.10	**1.34**
4 - BCS 92 w.Adv.Eng. (Rdyne)	n	1.0	7	1.1	2	1.00	1.0	1.00	**1.10**
5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	n	1.0	7	1.1	2	1.00	1.0	1.00	**1.10**
6 - HTHL SSTO ESJ (GT Hyperion)	n	1.0	5+4	1.2	2	1.00	1.1	1.00	**1.32**
7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lepsch)	n	1.0	9	1.2	2	1.00	1.0	1.00	**1.20**
8 - HTHL SSTO w.LACE (LaRC/Petley)	n	1.0	4	1.0	0	0.95	1.3	1.00	**1.24**
9 - HTHL SSTO w.MHD (Anser/Chase)	n	1.0	1	0.8	2	1.00	1.5	1.00	**1.20**

Table 1-11 Headcount Adjustment Factors as Modified by TPS and Engine Processing Factors

COST ADJUSTMENT FACTORS - OCM HC ESTIMATES REDUCED BY __ COMPARED TO STS/ELV											
	ATS BCS	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL SSTO Rocket w/LA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich))	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)	9 - HTHL SSTO w.MHD (Anser/Chase)
TPS PROCESSING COMPLEXITY	**1.09**	**0.46**	**0.43**	**0.16**	**1.34**	**0.47**	**0.42**	**0.22**	**0.35**	**1.85**	**0.00**
ENGINE PROCESSING COMPLEXITY	**1.21**	**1.39**	**1.10**	**1.09**	**1.34**	**1.10**	**1.10**	**1.32**	**1.20**	**1.24**	**1.20**
LAUNCH OPERATIONS											
VEH PROC	0.37	0.52	0.52	0.58	0.37	0.57	0.58	0.58	0.46	0.38	0.66
PROC ENGR	0.09	0.52	0.52	0.58	0.37	0.57	0.58	0.58	0.46	0.38	0.66
RECOV OPS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FIXED SUPT	0.00	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
FACIL O & M	0.50	0.50	0.45	0.50	0.45	0.50	0.50	0.50	0.40	0.50	0.50
BASE SUPT	0.50	0.50	0.45	0.50	0.45	0.50	0.50	0.50	0.40	0.50	0.50
FLIGHT OPERATIONS											
FLT PLANNING	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
MISS S/WARE	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20
SIM/TRNG	0.30	0.75	0.50	0.75	0.75	0.75	0.75	0.75	0.50	0.75	0.75
MIS CTL O & M	0.30	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
SYS INTEGR	0.37	0.52	0.52	0.58	0.37	0.57	0.58	0.58	0.58	0.38	0.66
P/L ANALY INT	0.30	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
CREW OPS	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
FIXED SUPT	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
OTHER	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The resulting COMET/OCM headcounts, total operations costs and operations costs by flight for the four flight rates examined are shown in Table 1-12 and Figure 1-4. Based on the vehicle and mission characterizations indicated above, the HRST concepts fell into 3 distinct groups insofar as estimated headcount required for launch and flight operations, which categories include all support functions as well. The RBCC concepts Argus (40K payload) and Hyperion (20K Payload), and the two all-rocket SSTO concepts BCS 183 and BCS 92 were the lowest and so close in quantity as to be indistinguishable given the probable accuracy of the estimates. There is no apparent difference in flight rate sensitivity among these three concepts.

Table 1-12 Headcount, Annual Cost and Cost/Flight by Flight Rate

	CONCEPTS	ATS BCS	1 - VTVL SSTO RBCC (Kaiser Marq./Escher)	2 - HTHL SSTO Rocket w/LA (Woodcock)	2a - HTHL SS w.LA SERJ (GT Argus 40)	3 - HTHL SS w.LA RBCC (BNA-C. Ehrlich)	4 - BCS 92 w.Adv.Eng. (Rdyne)	5 - BCS 183 w.Adv.Eng & Mat. (Rdyne)	6 - HTHL SSTO ESJ (GT Hyperion)	7 - VTHL TSTO LO-Kero Reuse.R. (LaRC/Lipsch)	8 - HTHL SSTO w.LACE (LaRC/Petley)
	FLIGHT RATE 1	4,201	3,375	3,384	2,709	4,510	2,842	2,767	2,625	3,696	4,486
HEADCOUNT	FLIGHT RATE 2	5,173	3,874	4,159	3,301	5,600	3,479	3,423	3,192	4,557	5,573
	FLIGHT RATE 3	5,943	4,430	4,772	3,766	6,456	3,985	3,871	3,637	5,238	6,426
	FLIGHT RATE 4	6,575	4,888	5,280	4,150	7,161	4,401	4,275	4,005	5,801	7,128
	FLIGHT RATE 1	709	567	570	455	754	482	468	445	640	749
ANNUAL COST	FLIGHT RATE 2	886	662	710	562	945	600	591	550	814	938
M$97	FLIGHT RATE 3	1,030	766	823	648	1,096	697	674	636	959	1,089
	FLIGHT RATE 4	1,151	853	919	721	1,223	780	752	709	1,084	1,214
	FLIGHT RATE 1	14.17	11.34	11.40	9.10	15.09	9.64	9.35	8.89	12.81	14.98
COST PER FLIGHT	FLIGHT RATE 2	8.86	6.62	7.10	5.62	9.45	6.00	5.47	5.50	8.14	9.38
M$97	FLIGHT RATE 3	6.86	5.10	5.49	4.32	7.31	4.65	4.49	4.24	6.39	7.26
	FLIGHT RATE 4	5.75	4.26	4.60	3.60	6.12	3.90	3.76	3.54	5.42	6.07

One difficulty in assessing the meaning of this result arises upon consideration of the Hyperion vehicle's lower payload capacity (20K). Since the estimates were made at the same flight rates for all concepts, Hyperion is not penalized for having to fly much more to achieve the same annual delivery of tonnage to orbit. Further, since total tonnage delivered in not only a factor of payload capacity but market driven payload weights and multi-manifesting, a simple ratio of flight rates would not resolve the difference. Suffice it to say here that since the difference in headcount is not very large, Hyperion would probably suffer greatly by comparison in driving up the headcount to process a flight rates to match the delivered tonnage to orbit of the other three concepts. However, it does appear that Argus and the two all-rocket concepts offer a better a substantially higher probability of lower operations costs of all the concepts examined. It is significant that not one of these three are more sensitive to flight rate than the other two. The next group consists of the VTVL SSTO RBCC (Escher), HTHL all-rocket with Launch Assist and VTHL TSTO rocket. These three are more spread, so that the Kaiser Marquardt VTVL RBCC appears to offer an advantage as the flight rate increases. This results from an apparent lower sensitivity to flight rate effects for the KM concept. Again, other than that benefit accrued to KM, there is little to distinguish among these three. In annual costs, the relation between the KM and the HTHL All Rocket w/LA concepts remains constant, while the gap between them and the TSTO Rocket widens, due in part to propellant costs and greater facilities maintenance burden. In Annual Cost, the TSTO begins to close with the higher three concepts. These three concepts group themselves with the higher processing and support headcounts required. The headcounts and costs of the two RBCC NASP derived vehicle (NDV) type concepts are almost identical, which should not be surprising given the manner in which concept characterizations are entered in COMET/OCM.

Application of launch assist did not appear to be a determinant factor. One RBCC vehicle with launch assist had the lowest projected costs. An all rocket SSTO had mid-range costs.

Another RBCC with launch assist had the highest costs. The role of launch assist in enhancing performance, reduction of vehicle dry mass and increase in margin could not be assessed using COMET/OCM.

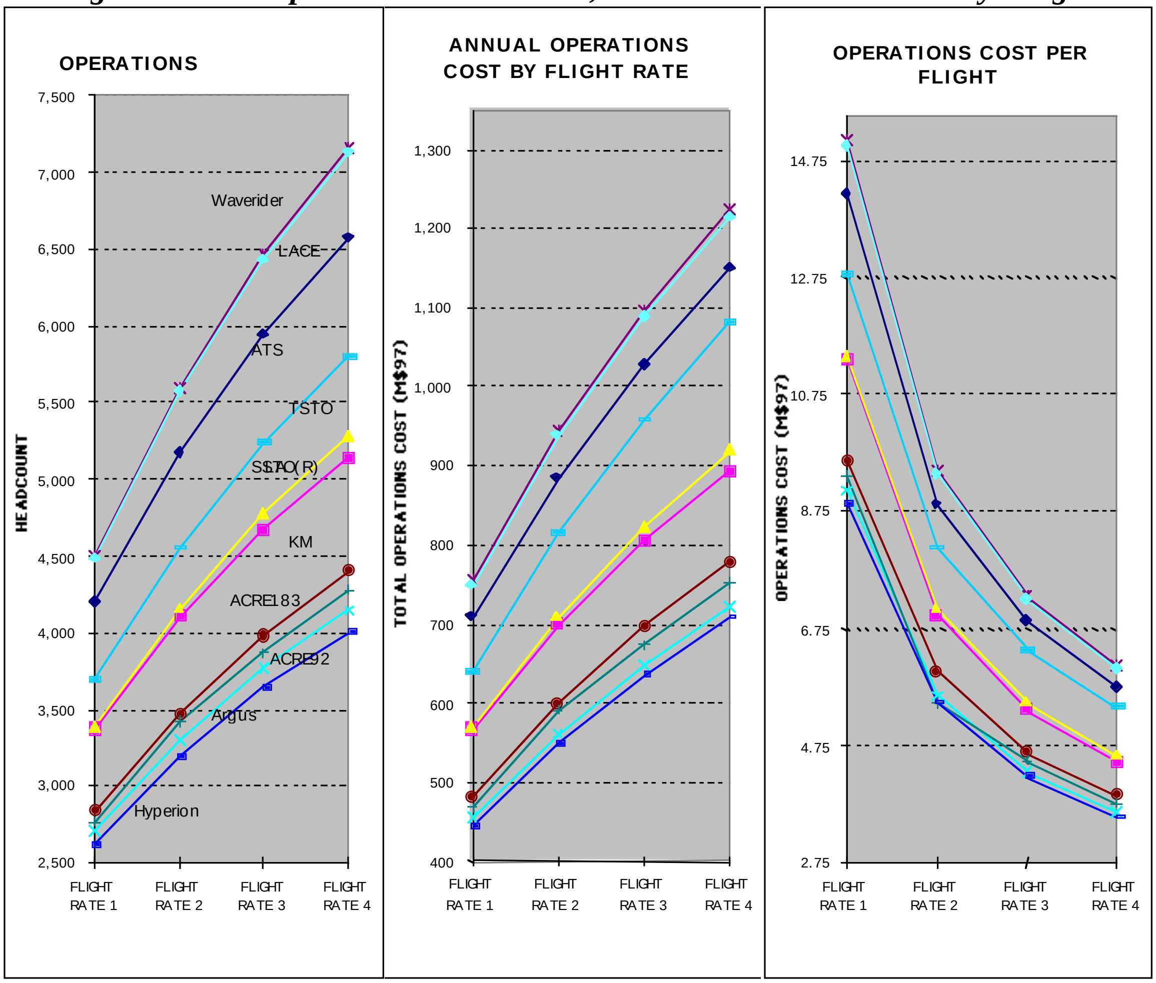
It must be stressed here that, as stated above, COMET and OCM were developed as tools to be applied in the preliminary stages of concept exploration, when very little operations data are available. Therefore, the results in headcount and dollars should be viewed as relative comparative measures, not as point estimates of operations costs. It is to be hoped that the headcounts and therefore operations costs can be greatly reduced from the estimates shown through maturation of technologies and design improvements. The use of these two tools was intended to allow an assessment of the relative relationships among the concepts regarding probable operations costs.

1.5 RECOMMENDATIONS

Further study of one or more of the following concepts is recommended: an Argus class RBCC vehicle; a low maintenance, lightweight engine all rocket vehicle; a VTVL RBCC vehicle, and an all-rocket TSTO vehicle based solely on the results of the COMET/OCM analysis.

Launch assist may be applied to any of the Horizontal Takeoff (HT) vehicles but when treated as a core stage in the COMET analysis added to the processing and maintenance burden, increasing costs. Vehicle robustness as a result of increased margin through launch assist did not appear in this analysis.

Figure 1-13 Operations Headcount, Annual Cost and Cost by Flight



APPENDIX E - Architectural Assessment Results Assessing & Analyzing Advanced Space Transportation Concepts and Technologies

(Carey McCleskey & Russel Rhodes, Kennedy Space Center)

Method of Assessing Concept Architectures Against HRST Study Guidelines

All first-order architectural system concepts tend to be rather sketchy in nature. Complicating the assessment of such concepts, in this instance, is the fact that there is a lack of quantifiable reusable launch system operations benchmarks with which to construct accurate operations models. Therefore, the HRST Operations Integration Task Force (OPS HITF) utilized several methods for assessing the operational viability of HRST concepts.

One of these methods use quantitative techniques in a qualitative process to gain strategic investment insight. Specifically, the method provides insight for focused investment in technology R&D for the development of "leapfrog" gains in space transportation systems. Further, this method relates the recurring to non-recurring costs for both the acquisition and R&D phases, and will be described here.

The task force agreed that an assessment method was needed that had the following characteristics:

1. Criteria that can be *quantified* and *scored*
2. Traceable to the HRST CAN's Technical Requirements (§ 3.1, p. 22):
   - Primary Functional Objectives (§ 3.1.1, p. 22)
   - Desirable System Attributes (§ 3.1.2, p. 23)
   - Programmatic Boundary Conditions (§ 3.1.3, p. 26)
3. Preferably anchored to SPST products, e.g., *Design Guide*, Architectural Assessment Tool, which were derived by consensus with government/industry/academia representatives

The OPS HITF viewed its task of assessing the "operations" of HRST concepts within the broader view of the total life cycle of investments required to bring about affordable, highly reusable space transportation. The desirable attributes of a system concept's architecture (i.e., vehicle concept, ground support infrastructure, and operations concept) during all the programmatic phases (i.e., technology R&D, system acquisition, and operations) is captured under the overall term of *affordability*.

Many *programmatic factors* surface during the process of developing a commercially viable HRST concept—and then a set of *system attributes* emerge when bringing the whole system into affordable, highly productive operation. The former is characterized by the non-recurring investments required in technology maturation, system development, and testing (flight and ground). This phase includes investments in propulsion component testing, engine element testing, prototype vehicle (X and Y vehicles) as well as any necessary ground system technology maturation, development and testing. The system attributes relate to the recurring, or "fielded" system—which dominate the return-on-investment of a long-term operational reusable space transportation system. Pursuing true affordability will require a movement from access-to-space ascent performance optimization towards a new emphasis in the space transportation architectural design process—*solid attention to the attributes of operational effectiveness. (See Figure 1 on next page).*

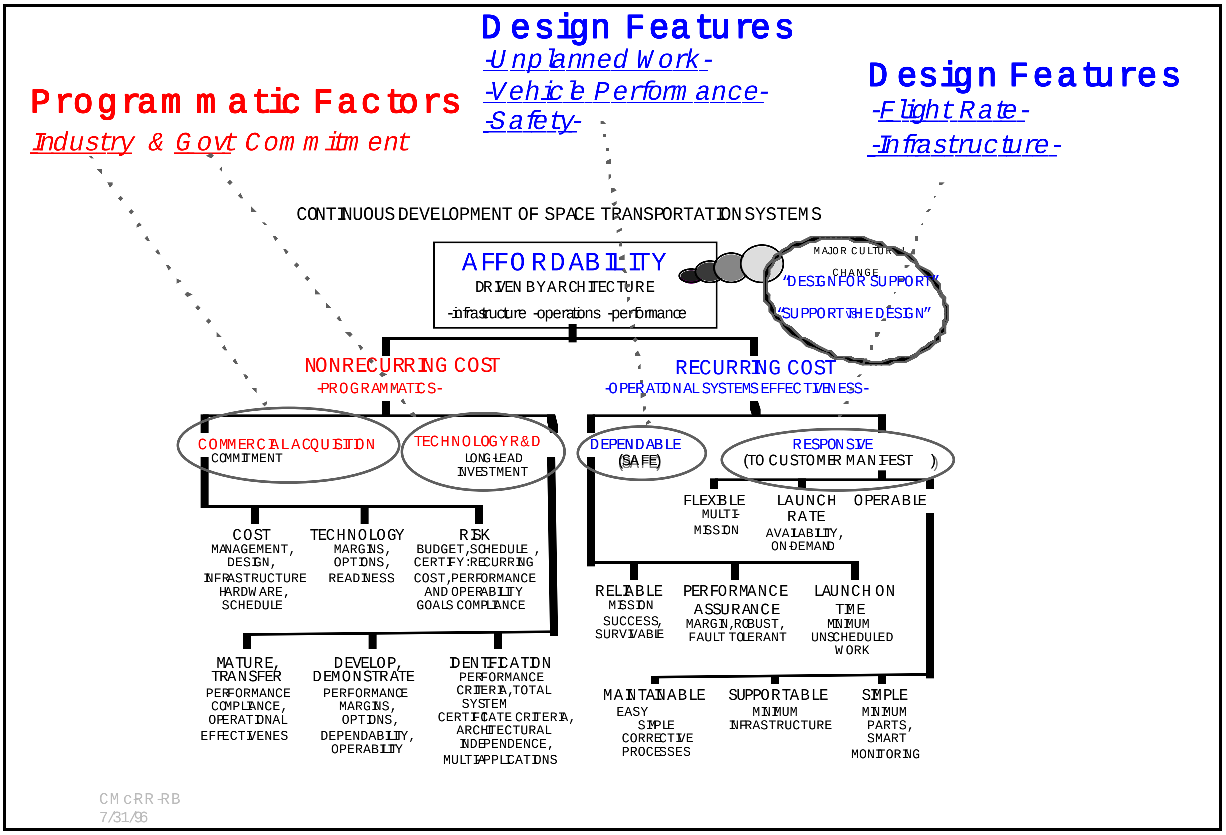


Figure 1—Map of Affordability Attributes Across the Programmatic Phases (Acquisition, R&T and Operations)

Architectural Assessment Tool

The *Architectural Assessment Tool* includes:

- An *Assessment Input Form* for concept designers to provide information necessary to perform a first-order assessment and derives an overall score in three assessment areas:

1. <u>Operational Effectiveness</u> (Recurring Benefit)
2. <u>Technology R&D</u> (Research and Development Programmatics)
3. <u>Program Acquisition</u> (Non-Recurring Programmatics)

- An electronic spreadsheet (Excel 7.0) that applies scores and weightings.

It is recognized that information regarding specific *design features* and *programmatic factors*, as noted in the *Guide for the Design of Highly Reusable Space Transportation*, are not traditionally available during early concept development. The Space Propulsion Synergy Team (SPST) created this assessment tool to overcome this lack of needed information for operational benefit as well as programmatic insight. The form was carefully constructed and is both anchored and traceable to the *Design Guide's* design features and programmatic factors and was approved with SPST's input and consensus.

The concept provider interacts with the tool through a series of assessment questions that are in a multiple-choice format for user-friendliness. The boxes receive a score value from one to ten (1-10). Each of the above three assessment areas receives an overall score, with the total of the three having a possible maximum value of one hundred (100). The maximum value items relating to the top box score in each question were designed to stretch the concepts towards the two orders of magnitude increase over currently operated systems as required by the HRST Study Guidelines (*see Appendix A*). Specific values for the scoring and weightings given to each assessment question are provided on the next page. A blank *Input Form* follows the scoring and weighting matrix. The Results section in the main body of the report supplied the order of magnitude weightings summary through applic*ation of a quadratic function:*

Order of Magnitude Score *= (Basic Score)**4/100000*

Assessment Results

The following HRST Study Concepts submitted Architectural Assessment Input Forms:

ACRE-183—Advanced Rocket Combustion Engine with Advanced Material—*(courtesy Mr. Dan Levack of Boeing/Rocketdyne, Canoga Park, CA)*

Argus—Twin-engine Rocket-Based Combined Cycle (RBCC) Vehicle with Mag-Lev Launch Assist—(*courtesy Dr. John Olds of Georgia Tech's School of Aerospace Engineering)*

BNA Waverider—RBCC-powered Waverider Vehicle with Mag-Lev Launch Assist—*(courtesy Mr. Carl Ehrlich/ BNA Space Systems, Downey, CA)*

TSTO—NASA Langley Research Center (LaRC) All Rocket Two-Stage-to-Orbit—*(courtesy Mr. Roger Lepsch, NASA Langley, VA)*

NASP-Derived Vehicle (NDV)—NASA Langley Research Center (LaRC) National Aerospace Plane (NASP) Derivative— *(courtesy Mr. Dennis Petley, NASA, Langley, VA)*

Vertical Take-Off/Vertical Land (VT/VL) SSTO—*Vehicle Powered by Rocket-Based Combined Cycle (RBCC) Engines Utilizing Super-Charged Ejector Scramjets—(courtesy Mr. William Escher, Kaiser–Marquardt, Van Nuys, CA)*

Additionally, the following concepts were included by the OPS HITF Team in conducting the assessment to help anchor the results on other reusable space transportation systems (existing and emerging):

STS—*Shuttle Space Transportation System (STS)*

ATS—*Access-to-Space Study, All-Rocket Single-Stage-to-Orbit (SSTO) with Hydrogen-Oxygen Cryogenic Propellant Only*

Hyperion—*Single-Stage-To-Orbit (SSTO) Rocket-Based Combined Cycle (RBCC) without Launch Assist*

> *As to be expected, the OPS HITF scores were more conservative than the Self-Scores. While showing potential for improvement, the current state of the overall preliminary scores reveal that the non-recurring system investment commitments are large in relation to the present state of the concepts' operational benefits.*

The OPS HITF team independently assessed and scored the nine systems referred to above and the basic results are displayed in *Table 1* and graphically plotted in *Figure 2*.

	OPERATIONAL EFFECTIVENESS Benefit Score from 10 from 1000	COMMERCIAL ACQUISITION Programmatic Score from 1 to 100	TECHNOLOGY R&D Programmatic Score from 1 to 100
	HITF Score	HITF Score	HITF Score
STS	***-- 14 --***	***-- 36 --***	***-- N/A --***
TSTO	38	35	52
NDV	53	17	20
BNA Waverider w/ Mag-Lev	55	18	23
ATS All-Rocket SSTO	***-- 60 --***	***-- 32 --***	***-- 46 --***
Hyperion RBCC SSTO	65	26	27
ACRE-183 (ATS w/ Advanced Rocket Engine)	74	15	50
Kaiser-Marquardt VT/VL SSTO	84	27	29
ARGUS Twin-Engine RBCC w/ Mag-Lev	**119**	23	29

Table 1—PRELIMINARY RESULTS of the OPS HITF HRST Architectural Assessment Using the SPST Architectural Assessment Tool

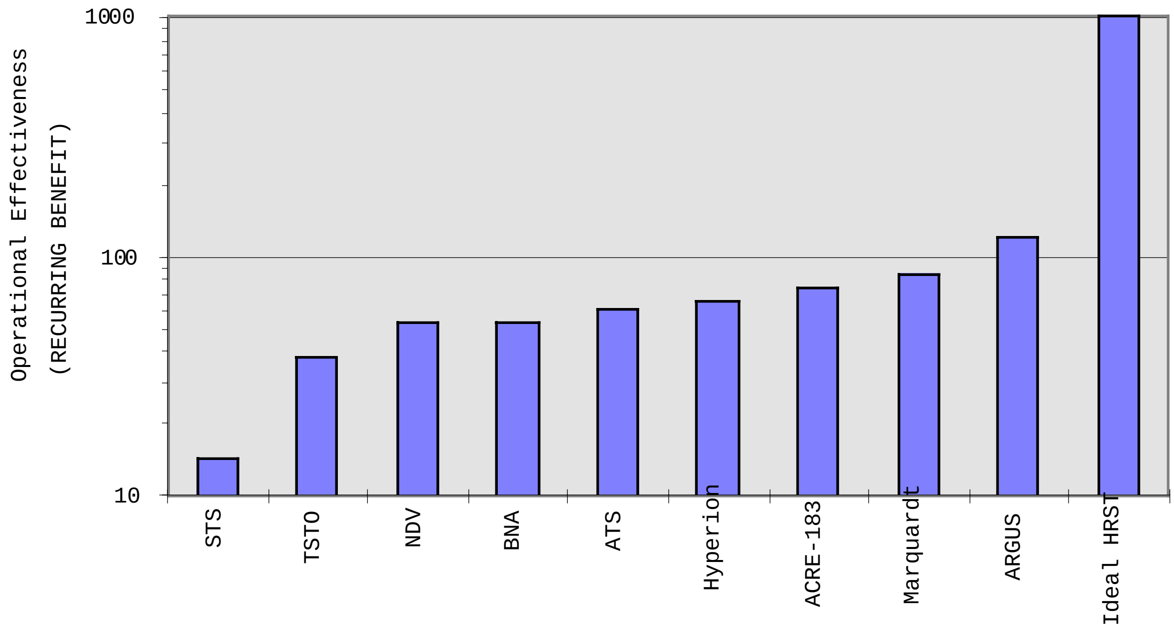


Figure 2—Preliminary HRST Study Concept Ranking (Per current concept definition)

The presently defined state of the HRST concepts roughly equates to the RLV Class ($1K/lb). One concept, however, did achieve crossing into the higher order quadrant—barely.

> *Based on the concept inputs, however, there appears to be reasonable potential for improvement into the HRST class through performance vs. operational margin trades. Use of some architectural guidelines and operability margin design <u>rules of thumb</u> should be explored to accomplish this.*

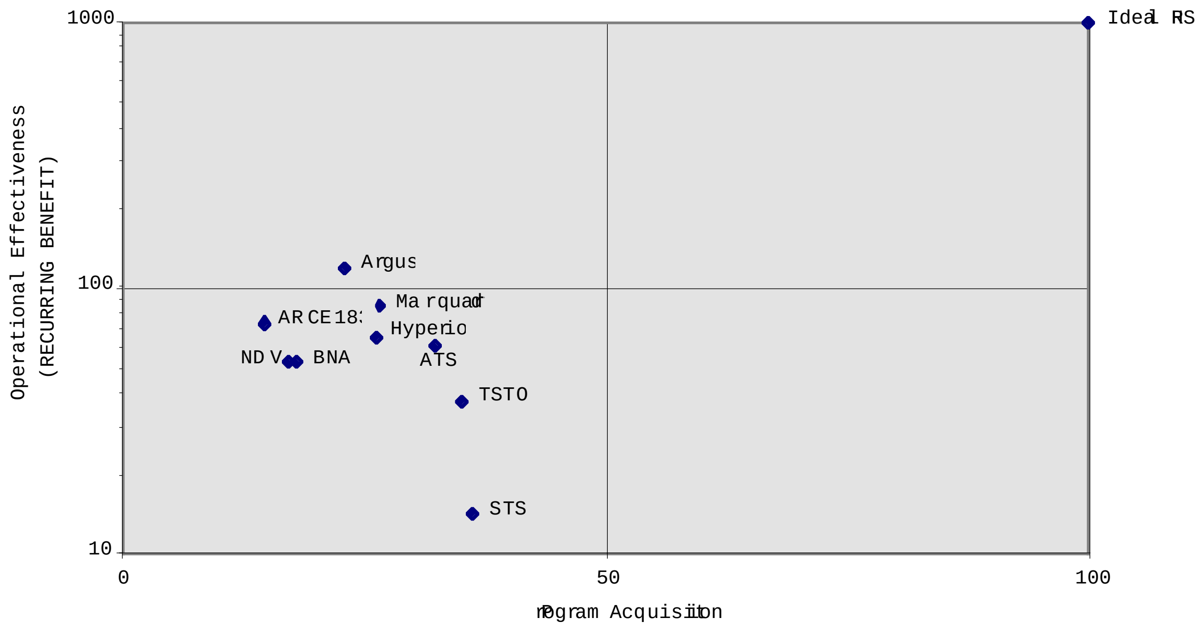


Figure 3—Present Operational Effectiveness vs. Non-Recurring Investment Commitment

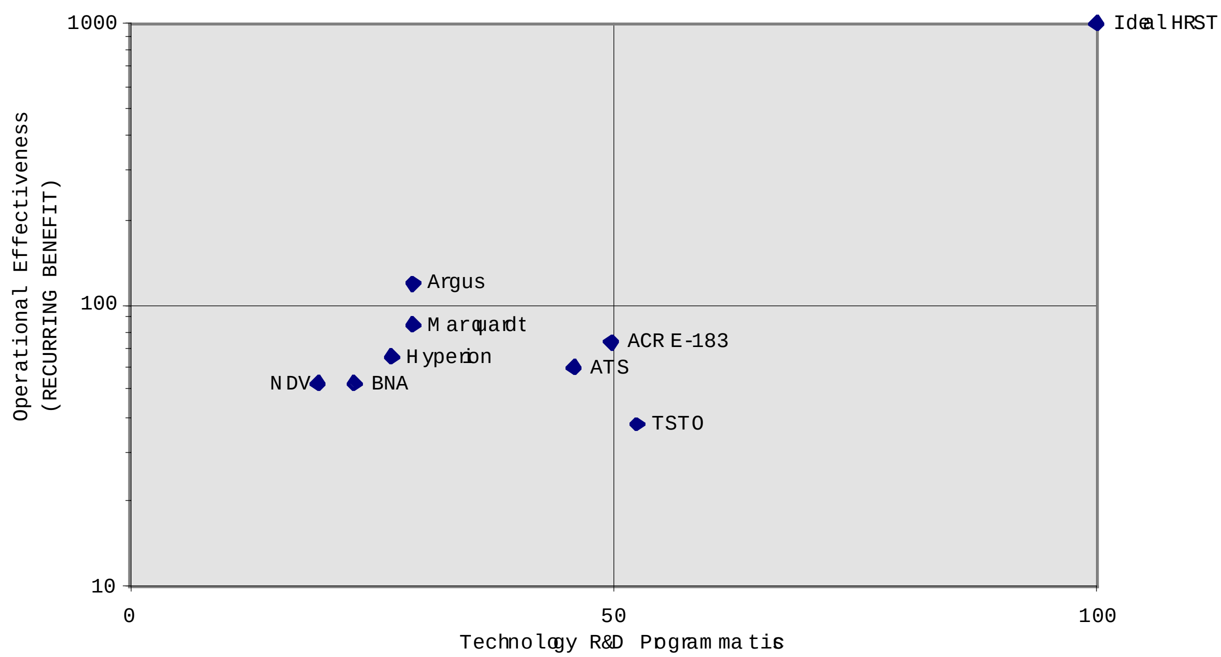


Figure 4—Present Operational Effectiveness vs. Technology R&D Non-Recurring Investment

Analysis of Assessment Results For Strategic Direction

Flight Rate Assessments

An exercise was performed during the analysis phase of OPS HITF effort to determine the operational labor levels associated with each concept per vehicle per flight according to six different weight categories (reference Appendix H). The Architectural Assessment Tool (AAT) was used to help derive relative O&M labor costs per flight per pound of vehicle dry mass. One unexpected result of this effort was that since the tool was anchored on STS labor values, and because determination of labor values is a function of flight rate (variable labor costs), it was found that the AAT could be used to assess concept flight rates. In fact, when using the AAT output scores for the concepts and extrapolating to the Access to Space (ATS) baseline, it was found that the flight rate per vehicle increased roughly according to the study criteria (i.e., that the baseline is roughly one order of magnitude more capable than STS and that the HRST threshold was somewhere near an order of magnitude over the ATS baseline. This result is shown below in Figure 5:

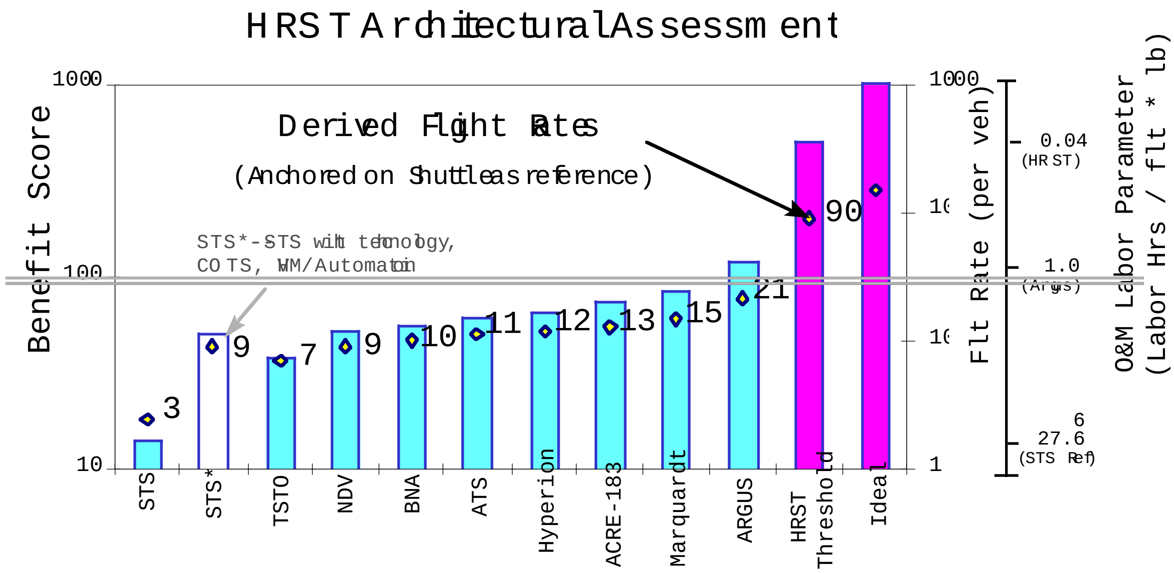


Figure 5—*Flight rate assessment of concepts as provided using the AAT.* (Note that the estimated threshold achieving HRST goals is on the order of 90 flights per year per vehicle. Guidelines estimated the flight rate at about 50 flights per year per vehicle).

> *Assessing, as opposed to allocating, flight rates for a given concept will be a critical skill in this era of affordable commercial space transportation development*

The importance of designing to flight rate can be seen from the Shuttle experience in the Figure 6 below. The Shuttle was originally conceived to have a flight rate of forty (40) launches per year out of Complex 39 with an Orbiter performance of 65,000 pounds per launch to LEO. This translates to "spacelift" performance of 2,600,000 pounds per year for the transportation system. The figure below shows the actual space lift performance, which closely track flight rate. Additionally, the actual vehicle performance came in at 50,000 lbs., roughly 75% of the expected vehicle performance. At 50,000 lbs. of vehicle performance, and assuming the system had actually achieved a flight rate of 40 per year, one can clearly distinguish the separate effects of trading operability for vehicle performance.

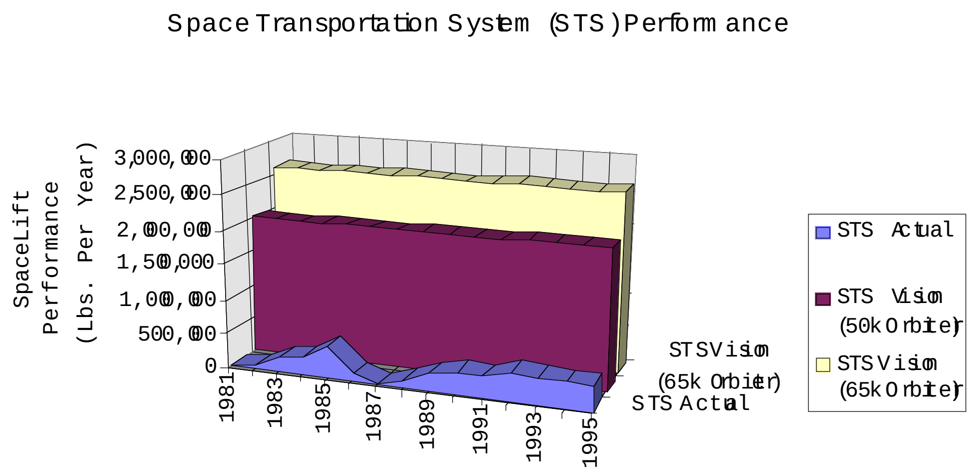


Figure 6—STS Performance with flight rate taken into account. The vehicle performance shortfall of 25% was small compared to the performance shortfall in flight rate. System dependability and responsiveness are the key attributes to focus on during conceptual design to avoid this type of severe performance shortfall.

Operational Benefit of Conducting a Comprehensive R&T Program

If it is assumed that the technologies within each concept were matured to the maximum extent (through a rigorous technology R&D effort), the question arises as to what would happen to the programmatic scores for the Commercial Acquisition quad chart (Figure 3).

To perform this exercise, a scenario was run where the scores for the questions 6, 15, 16 (which addressed reliability/dependability, use of COTS in the architecture, and use of Vehicle Health management in the architecture); as well as questions 19, 20, 23, and 24 (which addressed technology maturity in an acquisition programmatic sense). These scores were set to a vale of ten (10) across the concepts for this scenario. The chart in *Figure 7* displays the result:

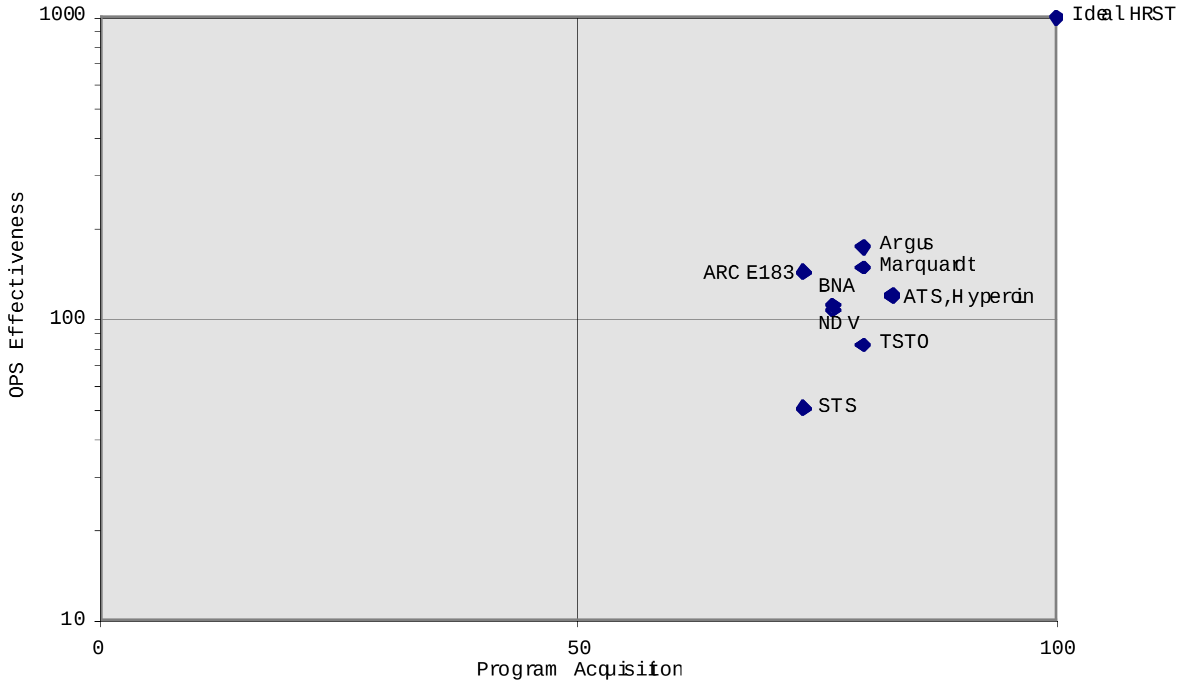


Figure 7—Consequences of Maturing Technology, Assuming Full Utilization of COTS Products in the Concept Architectures and its Effect on HRST Commercial Acquisition Viability

> *The result shows that the HRST Study guidelines can produce concepts that have the potential to achieve more affordable results. It should be emphasized that the concepts need another iteration to understand the potential to reach the cost per pound objectives. Once this confidence is gained, a vigorous R&T Program that focuses on operational effectiveness and commercial acquisition goals is required.*

Summary of Analysis

Packaging and Integration: The concepts reviewed, although integrating the rocket and airbreather in RBCC type concepts, did not integrate the secondary and main propulsion systems. Rocket systems with orbital maneuvering, reaction control and main propulsion systems are highly non-integrated. Future developments must more readily address propulsion technology integration that reduces interfaces, separate tanks, etc.

Importance of Hardware and System Reliability/Dependability: In order for a space transportation system to meet the HRST goals of $100s/pound, very high degrees of dependability must be achieved. Hardware replacement costs must average to be a small fraction of a percent per flight, keeping the vehicle out of the hangar, increasing its commercial utilization, i.e., flight rate is an absolutely critical parameter for commercially viable space transportation.

Importance of COTS: Key to the assumptions in assigning high score values to the above process was full use of commercial-off-the-shelf (COTS) products—even if choosing COTS is not the lowest weight option. The performance gain in using COTS due to the higher vehicle utilization will be the better trade. Of course, many subsystems currently used in space transportation systems will require intensive research and development with DDT&E program verification in order for the majority of components and software to become commercially available. This is a must, however, for attaining the order-of-magnitude affordability scores seen in Figure 4.

Development of Vehicle Health Management Technologies: To attain the performance seen in Figure 4, the continued development of Vehicle Health Management (VHM) technologies is required. Critical in this area is the use of non-intrusive instrumentation to overcome the tremendous amount of unplanned maintenance that occurs between flights of functionally complex vehicles, such as a reusable launch vehicle-particularly a highly reusable launch vehicle.

RECOMMENDATIONS

<u>Recommendation 1:</u> Architectural Guidelines: Architectural, global optimization of designs is required to achieve HRST goals. Optimization at component or sub-system levels must be only one part of a broader improvement strategy focused on affordable architectures. Large-scale optimizations which rethink major design decisions must be improved upon across the board to achieve HRST goals. The Ops Team developed a set of "Architectural Guidelines" which expand on the need to optimize designs and technology around broad, global features. The Guidelines are derived from the work of the Space Propulsion Synergy Team (SPST), a multi-industry-NASA-academia and government-entrepreneur group. This work by the SPST was in support of the HRST project. After performing the assessments of each architectural concept that was provided by the developer, it was recognized that there is a need to optimize each concept to increase its operational effectiveness (better reach the objective of recurring cost at $100 to $200 per pound to orbit). This should be accomplished by performing an iterative conceptual design process using some general principles as guidance to derive a more effective architecture. This can and should be applied until the concept is either optimized or reaches the objective. It is further recognized that mass fraction (weight margin) may be, or must be, compromised to apply these guidelines; however, the results may be surprising in some cases. These are listed in order of effectiveness of reducing the operations burden:

1. <u>Guideline</u>: *Fluid selection for ease of operability & supportability*

a. Avoid use of fluids that are toxic and require ground handling controls for personnel protection or environmental control reasons.

b. Avoid use of fluids that are flammable, other than for propellants purposes, to avoid need for additional fire protection at various ground stations

Benefits: Increases safety, operability and required support which results in less manpower, faster vehicle turnaround and lower recurring cost

2. Guideline: *Fielded margin (that which remains upon completion of the space transportation system acquisition) increased for mission flexibility and improved operational effectiveness*

a. Provide fielded margin in all vehicle system disciplines to allow customer and space transportation system mission flexibility

b. Use some of this fielded margin to increase the operational effectiveness, i.e., trade increased weight in some cases for concept trades that improve operational attributes like dependability (use of COTS) or better functional integration to delete large ground infrastructure support at launch site and manufacturing

Benefits: Increased mission flexibility of the space transportation system to better meet the customer's needs. Allows system trades on the concept design that increase potential of meeting the recurring cost objectives and engendering space market growth

3. Guideline: *Increase the vehicle and ground systems health management capability to allow increased space transportation system responsiveness to customer needs and labor reductions to provide reduced recurring cost.*

a. Provide BIT/BITE for all vehicle and ground systems (electrical, mechanical & structural) components. Embed fully automated routines that reduce ground turnaround time, labor and hands-on activities required to operate, verify component integrity, as well as perform troubleshooting and retest following corrective action/maintenance.

b. Provide built-in sensing network systems to allow automated inspections of all structural, TPS, and mechanical systems (which traditionally are inspected manually).

Benefits: Systems that are fully automated (flight and ground) will decrease vehicle turnaround, increase vehicle availability, reduce hands-on activities and collateral damage, reduce labor required and achieve large reductions in recurring cost. Avoids major out-of-service inspection operations.

4. Guideline: *Design for passive environmental control and avoid hazardous confined spaces-or confined spaces that require personnel entry (both planned and unplanned).*

a. Design system layout so that component change-out can be accomplished without entry into confined spaces

b. Provide airframe design to allow both ground and flight environments to be controlled through a passive design means. This avoids closed, hazardous confined spaces that must be maintained safe using active systems (GN2/air purge and hazardous gas detection systems).

Benefits: Delete need for large amounts of ground infrastructure to purge confined spaces. Infrastructure eliminated includes: purge air systems for personnel needs, purge systems of the same area with GN2 for flammable/detonable gases, hazardous gas detection systems, and personnel access kits. Added operational benefit in terms of responsiveness include elimination of personnel entry & control for safety. For example, mid-body and aft closed compartments can cause collateral damage and unplanned work if system hardware is not located on walls with external access. Elimination of closed/confined spaces, therefore, reduces manpower required, less ground turnaround time (greater flight rate capability per vehicle), reduced logistics tail for replacement parts and supplies, less ground infrastructure to operate and maintain, safer environment for personnel operations-all resulting in greatly reduced operations cost. Also reduces acquisition cost of both flight and ground hardware and associated facilities.

5. Guideline: *Provide an ideal overall propulsion packaging architecture that results in minimum hardware support requirements and flight-to-ground interfaces while also yielding the most reliable/dependable space transportation system*

a. Provide common integrated single vehicle propulsion system that performs the main ascent propulsion function (MPS), the on-orbit/de-orbit propulsion function (OMS), and the non-and rarefied atmospheric reaction control system (RCS) function. For operational improvement these functions must utilize only one set of propellant tanks, with only one set of ground support servicing systems. For example, the OMS can be to supplied from the main propulsion feed manifold sized for this function, and the RCS could be fed from the ullage gases supplied using an automated compressor/accumulator gas system

b. Provide for integration of electrical power generation (fuel cells/turbo-alternators) and any active thermal management of on-board systems with the integrated propulsion single set system. These functions should be supplied by ullage gases from the main propellant tank set using an automated compressor accumulator gas feed system

c. Provide propulsion sizing to accommodate all requirements with minimum number of engines (two engines ideal but no more than four)

Benefits: Deletion of functionally redundant systems, i.e., separate propellant tanks, pressurization systems, pneumatic controls, flight-to-ground umbilicals, avionics support for tanks fill & drain values, and very large ground support infrastructure at the launch and manufacturing sites. Large reduction in parts count and support logistics. Also allows the use of non-usable residual gases from traditional concept. Results in large reduction in manpower, replacement hardware cost, reduction in sustaining engineering and manufacturing support. Net benefit is faster turnaround (more responsive and available transportation system) more reliable/dependable system (less systems and backup systems) and large reduction in recurring cost. Also should result in less acquisition cost.

6. Guideline: *Provide a space transportation system with minimum unique stages (flight and ground) and design-to interfaces*

a. Provide a very integrated single stage concept with only one set of propellant servicing interfaces and only one power interface to ground

b. Provide propulsion system with minimum interfaces to vehicle, i.e., provide integrated propulsion system to allow minimum functional requirements like main propellant pumps placement with main tank to eliminate chilldown and conditioning requirements to operate the main engines. Also placement of the main LOX tank in aft end to eliminate complex and time-consuming servicing requirements like chilldown, anti-geysering and pogo systems for flight.

c. Provide simplified payload to vehicle such that there are a minimum support and functional requirements, i.e., only structural attachments also same attachments for every flight and payload accommodations. Enclosure provides any unique support, i.e., contamination control, electrical power, data management, fluid services and purge (if needed) or even life support if personnel are included.

<u>Benefits</u>: Will reduce the number of ground processing/checkout stations, assembly and integration station(s), and very large amount of unique ground support equipment. Will also greatly reduce the number of manufacturing and stage assembly facilities. Will result in a very large reduction in logistics of consumables, replacement parts, and labor headcount. Will achieve much shorter ground turnaround time (higher single vehicle flight rate capability) that results in a large reduction in acquisition and recurring cost.

7. <u>Guideline</u>: *Provide a space transportation system that is simple, i.e., very small number of manufacturing, test, and operations facilities, with only a minimum number of different/complex parts, often resulting in active ground servicing requirements*

a. Provide a simple highly integrated/automated single stage vehicle.

b. Provide a simple highly integrated/automated single stage vehicle without launch assist or active ground systems to accommodate launch acoustic, cooling, and ignition overpressure environments

<u>Benefits</u>: A simple single stage space transportation system will achieve large reductions in manufacturing, special test and launch facilities. In addition, the resulting unique ground support equipment associated with multi-stage concepts are eliminated, providing shorter ground turnaround time, less labor headcount, more available and responsive system to payload customer needs, and a large reduction in acquisition and recurring cost.

8. <u>Guideline</u>: *Provide a simple vehicle with a minimum number of different fluids or gases with unique vehicle-to-ground interfaces*

a. Provide a vehicle system that only requires a single set of fluids to accommodate all functions for the space transportation system

b. Provide a vehicle system that only requires one single gas on-board that accommodates all functions required.

c. Provide a vehicle that does not require on-board purges and also no purges to maintain safe vehicle on the ground during servicing for flight.

<u>Benefits</u>: Ground servicing will require only a few ground servicing systems resulting in very large reduction in ground servicing systems at several facility stations. This in turn achieves a large reduction in labor headcount, acquisition and recurring cost. Large reductions in logistics of replacement parts,

consumables, sampling, filtering and conditioning systems, labor and recurring cost and cycle time.

9. Guideline: *Provide a simple vehicle with a minimum number of ground electrical power servicing requirements*

a. Provide a flight vehicle system that provides its own power management on-board allowing only one vehicle-to-ground interface at each ground facility station

Benefits: Greatly reduced flight-to-ground umbilicals, ground servicing systems at each station, large reduction of parts, reduced logistics, reduction in labor headcount, more responsive transportation system, and large reduction in acquisition and recurring costs.

10. Guideline: *The space transportation system only uses highly reliable/dependable parts, components, and systems-and are ground and flight demonstrated/certified to be such during the development phase prior to system acquisition. Use of demonstrated highly reliable/dependable systems results in a fielded design that requires very infrequent unplanned maintenance.*

a. Select hardware that is commercial-off-the-shelf (COTS) and that has a very high demonstrated meantime between failure (even if the hardware isn' t the lightest weight-the resulting increase in flight rate will more than make up the weight difference of one launch)

b. The use of laser igniter and hydrostatic bearing turbopump technology will provide reduced stresses on rocket during start transition (no longer constrained to flammability limits) by decreasing the ramp-up rate. The new bearings will also provide greater MTBF.

c. Operate the rocket engines at reduced maximum designed power level

Benefits: A space transportation system that is very responsive and available in meeting customer needs at lowest recurring cost. Specifically, it results in a low level of logistics (including the rocket engine element) for replacement parts and minimum labor headcount, as well as a reduction in collateral damage from component replacement and troubleshooting on the vehicle.

11. Guideline: *Provide a space transportation system with only a few connections required to integrate the major functions and their components. (Avoid design-in potential leak connections, tubes, hoses, ducts, etc., for fluid and gas systems; and electrical mating connections, wiring, switch-gear, etc. for electrical power, data, command & control, communications systems)*

a. Provide designs that do not require leak testing verification for fluids and gases for both static and dynamic applications, i.e., nearly all-welded systems.

b. Provide designs for electrical power and data transmission without the use of thousands of cable connections providing potential failure resulting excessive, time-consuming troubleshooting, repair and restoration to flight certified condition.

Benefits: Much safer, more reliable, and simple system to operate. Also far less unplanned work, operations stoppage (cycle time, launch holds and scrubs, etc.) Results in lower recurring cost as well as faster acquisition schedules to bring the system through certification.

<u>Recommendation 2</u>: Building an Earth-to-Orbit (ETO) Technology Roadmap (Ground & Flight Demonstrators-"Pathfinders" & "Trailblazers")—The next step beyond HRST efforts should be to build a technology roadmap that defines a phasing plan for ground and flight demonstrations. However, the concepts, as provided, are not yet to a level of maturity for clearly determining which will achieve HRST goals. That being the case, a roadmap that leads to architectures achieving operating costs below $1,000 per pound is likewise premature. It is recommended that an iteration process be initiated on the provided concepts. The iteration process should be guided through the use of the suggested design "rules of thumb" (see below.) Once the concepts have reached maturity, or the HRST goals are assessed as having been met, then the nation will be ready to construct an ETO roadmap that leads to a portfolio of promising architectural concepts that are capable of achieving $100-$200 per pound cost. In the context of these promising architectures, the technology requirements could then be formulated.

<u>Recommendation 3</u>: Concept Programmatic Information Needs to be Better Identified and Clearly Separated Between R&T and Commercial Acquisition Commitment Phases—As the iterative process unfolds, better definition of cost and schedule should be made available. Particularly needed, however, is clear discrimination between which are incurred during the research and technology phase, and which are incurred during the commercial acquisition phase. This clear discrimination is required to build an effective research and technology program that reduces high cost and risk investments associated with commercial acquisition.

<u>Recommendation 4 (Final Recommendation to HRST Study Team)</u>: Avoid Presenting Premature Architectural Selection—Premature architectural concept selection at this point will lead to a programmatic commitment that would fall well short of the Civil Space Transportation Study goal of engendering space market growth.

Architectural Assessment Form

Highly Reusable Space Transportation
Architectural Assessment Form

Characterizing Reusability and Afford
Transportation System Concepts

Shuttle System Reference

Each HRST Architectural Concept provides a generic Summary Sheet for communication and assessment

Concept Title: ___________________________

Identify the overall *propulsion concept* for assessment:

o All Rocket
o Combination Cycle
o Rocket-Based Combined Cycle (RBCC)

o Launch Assist/All Rocket
o Launch Assist/RBCC
o Launch Assist/Combination Cycle

o Microwave Beaming
o Very Advanced (Specify)

Notes:

Each numbered assessment category contains a cross-reference to particular design feature(s) that may be found in the Space Propulsion Synergy Team's *A Guide for the Design of Highly Reusable Space Transportation*, August 29, 1997. (e.g., designations such as *DF #6*). This guide contains more specific information regarding the assessment items in this form.

Designations of "STS" or "ATS" on the assessment form indicate the current state-of-the-art in each numbered assessment category.

STS — refers to the Space Shuttle (Space Transportation System) baseline

ATS — refers to the Access-to-Space study (Option 3) all-rocket single stage to orbit (SSTO) vehicle reference (the HRST study project's reference vehicle)

Part 1.1
Operational Effectiveness Assessment

Each numbered assessment category in Part 1.1 contains a cross-reference to particular design feature(s) (DF) that may be found in the Space Propulsion Synergy Team's *A Guide for the Design of Highly Reusable Space Transportation*, August 29, 1996, (e.g., designations such as *DF #6*). This guide contains more specific information regarding the assessment items in this form.

Designations of "STS" or "ATS" on the assessment form indicate the current state-of-the-art in each numbered assessment category.

STS — refers to the Space Shuttle (Space Transportation System) baseline

ATS — refers to the Access-to-Space study (Option 3) all-rocket single stage to orbit (SSTO) vehicle reference (the HRST study project's reference vehicle)

1. Overall propulsion packaging architecture—(DF#6):

	All propulsion systems totally integrated with one set of tanks
_____	Partially integrated propulsion systems
_____	(STS/ATS) Separate systems, such as, MPS, OMS, RCS, Power drivers, etc
_____	Main propulsion system definition addressed—remainder TBD
_____	Current definition of concept insufficient to determine

2. Main propulsion packaging architecture—(DF#26):

	One main propulsion engine element
	Two main propulsion engine elements
_____	(STS) Three main propulsion engine elements
_____	Four main propulsion engine elements
_____	Five main propulsion engine elements
_____	Six main propulsion engine elements
_____	(ATS) Seven main propulsion engine elements
_____	More than seven main propulsion engine elements
_____	Current definition of concept insufficient to determine

3. Main propulsion operating dynamic events & operating modes excluding start-up & final shutdown (e.g., staging, mixture ratio changing, throttling, mode changes like low speed to high speed system) —(DF#15):

_____	No active engine system required to function during flight (i.e., no moving parts—Redstone, Jupiter, Thor-like)
_____	(ATS) Active engine throttle systems required to function during flight
_____	(STS) Multi-stage separation, throttling & early single-engine shutdown dynamics
	Active engine throttling systems with variable engine geometry nozzles
_____	Active engine inlet geometry & mode changes
_____	Current definition of concept insufficient to determine

4. Space Transportation System material selection—(DF#23):

	Architectural concept requires no use of pollutive or toxic materials
_____	Architectural concept requires no use of pollutive or toxic materials on the flight vehicle and ground servicing operations, but may use a few during manufacturing, assembly, cleaning operations
_____	Architectural concept requires no use of pollutive or toxic materials on the flight vehicle, but may use a few during manufacturing, assembly, cleaning & ground servicing operation
_____	(STS) Architectural concept requires use of pollutive or toxic materials on the flight vehicle, but may use a few during manufacturing, assembly, cleaning & ground servicing operations—into the atmosphere during flight, and requires much cleanup at launch site following launch (along with toxic waste management and disposal)
_____	(ATS) Current definition of concept insufficient to determine

5. Structural interface architecture (# of stages and design-to interfaces) (DF#7, 3):

	Single stage w/ integral propulsion system (including tanks) and with no element-to-element interfaces—no stand alone engine & no separate aeroshell
_____	(ATS) Single stage w/ non-integral propulsion system and with vehicle element-to-element interfaces—stand-alone engine & no separate aeroshell
_____	Single stage w/ non-integral propulsion system and with vehicle element-to-element interfaces and non-integral tanks (aeroshell concept)
_____	(STS) Multiple stages with many interfaces
_____	Current definition of concept insufficient to determine

6. Conceptual approach for reliability & dependability —(DF#10, 16):

_____	Uses only commercial-off-the-shelf (COTS) w/ demonstrated highly reliable components
_____	Uses a mix of COTS & custom, minimum weight-driven components with high technology maturity (TRL)
	(ATS) Uses a mix of COTS & custom, minimum weight-driven components with low technology maturity (TRL)
_____	(STS) Uses only custom minimum weight components
_____	Current definition of concept insufficient to determine

7. Concept for system/mission safety & reliability (Crit 1 = loss of life/vehicle, Crit 2=loss of mission) —(DF#25, 29):

_____	Transportation system has no "Criticality 1 or 2" failure modes (i.e., completely fault tolerant to support both mission success & total safety)
	Transportation system has no "Criticality 1" failure modes (i.e., completely fault tolerant to support safety of flight, but accepts mission failure through safe abort modes)
_____	Transportation system has a few "Criticality 1 and 2" failure modes (i.e., Crit 1's accepted by rationale and uses abort modes for safety, and Crit 2's accepted for loss of mission)
_____	(STS) Transportation system has many "Criticality 1" failure modes (accepted by rationale), accepts loss of mission, and additionally accepts loss of vehicle (1:500 flights probability)
_____	(ATS) Current definition of concept insufficient to determine

8. Transportation system vehicle complexity & safety dynamics (DF#12, 15, 19, 33, 39):

_____	Vehicle requires only a few active components to function during flight— requires no active systems to maintain safe vehicle (i.e., fail safe)— contains no active systems that require monitoring due to hazards which require corrective action to "safe" the vehicle
_____	Vehicle requires only a few active components to function during flight—requires no active systems to maintain safe vehicle (i.e., fail safe)—contains no more than three systems that require monitoring due to hazards which require corrective action to "safe" the vehicle
	Vehicle requires only a moderate number of active components to function during flight—requires a few active systems to maintain safe vehicle (i.e., fail safe)—contains a few systems that require monitoring due to hazards which require corrective action to "safe" the vehicle
_____	(STS) Vehicle requires many active components to function during flight— requires several systems to maintain safe vehicle (i.e., not-fail safe)— contains many systems that require monitoring due to hazards which require corrective action to "safe" the vehicle
_____	(ATS) Current definition of concept insufficient to determine

9. Space transportation system complexity—(DF#8, 20, 37):

______	Space Transportation with minimum number of flight systems, minimum ground support required, and overall parts count is controlled to a minimum
	Space Transportation that's complex—i.e., has single stage and some integration of similar or like functions to reduce number of systems and components—results in several systems and an elevated level of ground support infrastructure, with an associated level of parts count
______	(ATS) Space Transportation that's very complex—i.e., has single stage and no integration of similar or like functions to reduce number of systems and components—results in many systems and a large ground support infrastructure with a high parts count
______	(STS) Space Transportation that's extremely complex—i.e., has multiple stages and no integration of similar or like functions to reduce number of systems and components—results in many systems and a very large ground support infrastructure with a very high parts count
______	Current definition of concept insufficient to determine

**10. Space transportation maintainability (on-line operation, not depot-level repair)
(DF#32):**

	Single stage vehicle architecture permits component/element replacement requiring no personnel entry into vehicle and without the use of any special access kits, platforms and hardware, and will accommodate changeout and verification in no more than one hour—may not require propellant drain
______	Single stage vehicle architecture permits component/element replacement requiring no personnel entry into vehicle and without the use of any special access kits—allows external platforms and hardware, and will accommodate changeout and verification in no more than one hour after gaining external access—requires propellant drain
______	Multi-stage vehicle architecture permits component/element replacement requiring no personnel entry into vehicle and without the use of any special access kits—allows external platforms and hardware, and will accommodate changeout and verification in no more than one hour after gaining external access—requires propellant drain
______	Single-stage vehicle architecture that requires compartment entry, ground supplied purge system in air mode, installation of access platform hardware, removal of another system's components (which now lose their certification for flight) in order to gain access—all of the above only doable after vehicle is drained of propellant and "safed" (e.g., propellant tank and compartment purges, separation ordnance safely disarmed, etc.)
______	(STS) Multi-stage vehicle architecture that requires compartment entry, ground supplied purge system in air mode, installation of access platform hardware, removal of another system's components (which now lose their certification for flight) in order to gain access—all of the above only doable after vehicle is drained of propellant and "safed" (e.g., propellant tank and compartment purges, separation ordnance safely disarmed, etc.)
______	(ATS) Current definition of concept insufficient to determine

11. Fluid selection —(DF#1):

	Uses no toxic fluids in flight or ground system that restrict ground handling operations
_____	Uses no toxic fluids in flight or ground system that restrict ground handling operations at launch site—some toxics used for manufacturing, assembly and cleaning only
_____	(ATS) Uses no toxic fluids for flight minimum ground system restriction for on-line ground handling operations at launch site (like TPS water-proofing), except those that are serviced and sealed in off-line facilities—some toxics used for manufacturing, assembly and cleaning only
_____	(STS) Uses some toxic fluids for flight and ground operations
_____	Current definition of concept insufficient to determine

12. Number of different fluids & flight vehicle-to-ground interfaces —(DF#8, 12):

	Single stage vehicle with fully integrated design that only requires two fluids and stored in two tanks
_____	Multi-stage vehicle with fully integrated design that only requires two fluids and stored in two tanks per stage (common fluids between stages)
_____	Single stage vehicle with fully integrated propulsion design that only requires two fluids and stored in two tanks per stage, but has separate system(s) for other fluid system functions (e.g., active cooling)
_____	(ATS) Single-stage vehicle with separate tanks for each function & different fluids for each fluid (e.g., main propulsion = LH2/LO2 & orbital maneuvering propulsion = MMH/N2O4 & hydraulics & reaction control = MMH/N2O4 & environmental control working fluid = Freon 21 & other coolants = XXX & etc.)
_____	(STS) Multi-stage vehicle with separate tanks for each function & different fluids for each fluid (e.g., main propulsion = LH2/LO2 & orbital maneuvering propulsion = MMH/N2O4 & hydraulics & reaction control = MMH/N2O4 & environmental control working fluid = Freon 21 & other coolants = XXX & etc.)
_____	Current definition of concept insufficient to determine

13. Number of different gases & flight vehicle-to-ground interfaces —(DF#9, 7):

_____	Single stage vehicle that requires no on-board stored gases
	Single stage vehicle that requires only one on-board stored gas
_____	Multi-stage vehicle that requires no on-board stored gases
_____	(ATS) Single stage that requires many different gases for flight operations (e.g., GH2, GO2, GHe, GN2, NH3, etc.) which are stored in many separate vessels and each requiring flight-to-ground interfaces for servicing
_____	(STS) Multiple-stage that requires many different gases for flight operations e.g., GH2, GO2, GHe, GN2, NH3, etc.) which are stored in many separate vessels and each requiring flight-to-ground interfaces for servicing
_____	Current definition of concept insufficient to determine

14. Ground electrical power requirements for turnaround—(DF#8, 38):

_____	No vehicle ground power system required with minimized ground power infrastructure
	One vehicle ground power system required with minimized ground power infrastructure
_____	(STS/ATS) Many vehicle ground power systems required (multi-voltages, dc/ac, single-phase, multi-phases, etc.) resulting in large ground power infrastructure
_____	One vehicle ground power system required with ground power production infrastructure
_____	Current definition of concept insufficient to determine

15. Vehicle Health Management (VHM) capability (i.e., for all on-board systems including passive ones, such as thermal protection & structures) (DF#3, 13, 14, 22, 24):

_____	All systems—both passive and active—have BIT/BITE from on-board, with non-intrusive/non-mechanically active sensors only, requiring no hands-on or ground support aided activity—utilizing an architecture with minimum number of conductor paths, connectors, interfaces, etc.
_____	All systems—both passive and active—have BIT/BITE from on-board, with non-intrusive sensors only, requiring no hands-on or ground support aided activity—utilizing an architecture with minimum number of conductor paths, connectors, interfaces, etc.
	All systems—both passive and active—have BIT/BITE from on-board, with limited use of intrusive sensors, requiring no hands-on or ground support aided activity—utilizing an architecture with minimum number of conductor paths, connectors, interfaces, etc.
_____	All systems—both passive and active—have BIT/BITE from on-board, with limited use of intrusive sensors, requiring limited hands-on or ground support aided activity—utilizing an architecture with minimum number of conductor paths, connectors, interfaces, etc.
_____	(STS/ATS) Only traditional electrical functions have BIT/BITE (e.g., propulsion controller boxes, navigation & communications LRUs, guidance & control LRUs, data processing LRUs, etc.) — most mechanical hardware/systems require either hands-on or ground support aided activities to verify functional for flight
	Current definition of concept insufficient to determine

16. Concept for controlling fluid/gas leakage in the transportation system architectural design—(DF#11):

______	All fluid/gas systems use component connections that are maintainable, but require no process control (i.e., leak-checking) following removal & replacement (i.e., welded integrity)—remainder of system is all-welded construction
	All fluid/gas systems use component connections that are maintainable, with automated process control (no hands-on leak-checking) following removal & replacement without compromising maintainability—remainder of system is all-welded construction (no fittings and flanges between components for ease of assembly)
______	All fluid/gas systems use best traditional component connections that are maintainable, with automated process control (no hands-on leak-checking) following removal & replacement without compromising maintainability—remainder of system is all-welded construction (no fittings and flanges between components for ease of assembly)
______	STS Traditional techniques are used that require leak checks (i.e., process controls) and many fittings and flanges are used for ease of assembly
______	ATS Current definition of concept insufficient to determine

17. Environmental control—(DF#4, 9):

______	Flight vehicle aerodynamic architecture provides all needed environmental control without the use of closed compartments, removable heat shields, and ground support system aids—and without compromising safety on the ground or in flight
	Flight vehicle architecture provides adequate environmental control during flight without use of closed compartments and removable heat shields— but, requires ground support systems control during launch preparations and launch operations
______	Flight vehicle architecture provides adequate environmental control during flight with very few closed compartments with simple thermal protection—but not requiring ground support systems control during launch preparations and launch operations—and without compromising safety on the ground or in flight
______	(STS) Flight vehicle contains several closed compartments, removable heat shields, and ground support systems to provide environmental control, both on the ground and in flight
______	(ATS) Current definition of concept insufficient to determine

18. Fielded transportation system margin (i.e., for all on-board systems including passive ones, such as thermal protection & structures) —(DF#2, 18, 27, 40):

	Transportation system has a reasonable amount of fielded margin so as to provide payload flexibility (i.e., no performance margin assessments required operationally for flight) and growth, e.g., 15-20% (has positive operational margin)
_____	Average Isp and vehicle mass fraction require management assessment for flight performance margin before each flight, i.e., no real margin and little payload flexibility (has no operational margin)
_____	(STS) Lack of performance margin (required mass fraction) in the system, such that robustness and responsiveness are compromised on features such as on-board BIT/BITE VHM, subsystem simplicity, robust thermal protection (has negative operational margin)
_____	(ATS) Current definition of concept insufficient to determine

Programmatic Assessment
Part 1.2A—Program Acquisition

The numbered assessment questions in Part 1.2A have been developed by the HRST Operations Assessment Team to provide the Assessment Team additional insight to the programmatic factors of the concept as they relate to the HRST acquisition guidelines. As with the Operational Effectiveness parameters referred to by their "DF" designation in the first eighteen (18) questions (Part 1.1), these questions cross-reference programmatic factors in the *Design Guide*'s "Program Considerations" section.

19. Program Acquisition—Number of major new technology development items (*#1-PA*):

	There are no immature technologies required (flight or ground), i.e., technologies have demonstrated high reliability/dependability (flight and ground), compliance with all operational effectiveness functions (Part 1.1), and provides the required fielded margin.
	There are no immature technologies required (flight or ground), i.e., technologies have demonstrated high reliability/dependability (flight and ground) in a like environment, but have not demonstrated operational effectiveness functions other than reliability/dependability.
	(STS) There are no immature technologies required (flight or ground), i.e., technologies have been demonstrated in a like environment (TRL 6 and above), but have not demonstrated compliance with operational effectiveness functions.
	There are no immature technologies required (flight or ground), except one major technology at TRL 5. All other technologies have been demonstrated in a like environment (TRL 6 and above), but have not demonstrated compliance with operational effectiveness functions.
	There are no immature technologies required (flight or ground), except two or three major technologies below TRL 6. All other technologies have been demonstrated in a like environment (TRL 6 and above), but have not demonstrated compliance with operational effectiveness functions.
	There are more than three major technologies below TRL 6 (flight or ground) requiring demonstration in a like environment, and have not demonstrated any compliance with operational effectiveness functions.
	Current definition of concept insufficient to determine or outside programmatic boundaries.

List major new technologies:

20. Program Acquisition--Technology Readiness Level @ program acquisition milestone: TRL-6+margin (*#2-PA*):

	All technologies are at TRL-8 or 9 and have high demonstrated reliability and dependability (COTS)
	All technologies are at TRL-8 or 9 and have high demonstrated reliability/dependability but only 50% commercially available (COTS)
	(STS) All technologies are at the TRL-6 level and only some have demonstrated reliability/dependability, but many are commercially available (COTS)
	One major technology has not achieved TRL-6 but others are at TRL-8 or 9 and have demonstrated high reliability/dependability with many commercially available (COTS)
	More than one major technology has not achieved TRL-6 and all others are at TRL-8 or 9 and have demonstrated high reliability/dependability with many commercially available (COTS)
	Current definition of concept insufficient to determine or outside programmatic boundaries.

21. Program Acquisition—Infrastructure Cost: Initial system implementation (i.e., capital investment) (*#4-PA, #16-PA*):

	All infrastructure investment required for technology maturation provided for full scale manufacturing and test capability (i.e., are all available for acquisition phase @ no additional cost) and the launch, landing, logistics, payload processing, and transportation acquisition costs are estimated @ less than one-half billion dollars (**$0.5B**).
	All infrastructure investment required for technology maturation provided full scale manufacturing and test capability (i.e., are all available for acquisition phase @ no additional cost) and the launch, landing, logistics, payload processing, and transportation acquisition costs are estimated @ less than one billion dollars (**$1.0B**).
	Most infrastructure investment required for technology maturation is provided for full scale manufacturing and test capability (i.e., mostly available for acquisition phase @ no additional cost) and the launch, landing, logistics, payload processing, and transportation acquisition costs (including any additional developmental manufacturing & test infrastructure) are estimated @ less than one-and-a-half billion dollars (**$1.5B**).
	Infrastructure investment required for technology maturation did not provide for any available capability for full scale manufacturing and test capability for the acquisition phase. Therefore this investment for acquisition includes manufacturing, major test, launch, landing, logistics, payload processing, and transportation, and these acquisition costs are estimated at less than two billion dollars (**$2.0B**).
	(STS) All infrastructure investment required for technology maturation provided full scale manufacturing and test capability (i.e., are all available for acquisition phase @ no additional cost) and the launch, landing, logistics, payload processing, and transportation acquisition costs are estimated @ much greater than two billion dollars (**$>2.0B**).
	Current definition of concept insufficient to determine or outside programmatic boundaries.

22. Program Acquisition—Total system DDT&E (design, development, test & evaluation) and TFU (theoretical first unit) concept development and implementation cost (i.e., includes estimated first unit cost) (*#5-PA*):

	Combined DDT&E and TFU cost are less than one-half billion dollars (**$0.5B**). (This is achievable by accomplishing a very thorough R&D maturation program that demonstrates compliance to all performance and operational effectiveness parameters.
	Combined DDT&E and TFU cost are less than one billion dollars (**$1.0B**).
	Combined DDT&E and TFU cost are less than one-and-a-half billion dollars (**$1.5B**) with the TFU cost @ less than 20% of total.
	Combined DDT&E and TFU cost are less than two billion dollars ($2.0B) with the TFU cost @ less than 20% of total and the flight rate capability must exceed the required 200 flights per year
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

23. Program Acquisition—Technology capability margin (performance as fraction of ultimate) (*#7-PA*):

	All major technologies have been demonstrated far beyond the TRL-6, including the performance parameters, and operational effectiveness parameters with a resultant fielded margin of fifteen to twenty percent over intended operating requirements.
	Most major technologies (above 80%) have been demonstrated far beyond the TRL-6, including the performance parameters, and fifty percent (50%) of the major technologies have demonstrated operational effectiveness parameters with a resultant fielded margin of fifteen to twenty percent over intended operating requirements.
	Most major technologies (above 80%) have been demonstrated far beyond the TRL-6 including performance and less than twenty percent (20%) of the major technologies have demonstrated operational effectiveness parameters with a resultant fielded margin of fifteen to twenty percent over intended operating requirements.
	Most major technologies (above 80%) have been demonstrated far beyond the TRL-6, including the performance parameters, but have not demonstrated any operational effectiveness parameters. The performance parameters result in a fielded margin of approximately 15% over intended operating requirements.
	(STS) Most major technologies (above 80%) have been demonstrated far beyond the TRL-6, including the performance parameters, but with no definition of any margin over intended operating requirements.
	Current definition of concept insufficient to determine or outside programmatic boundaries.

24. Program Acquisition—Number of other technology options available at program acquisition commitment milestone *(#11-PA)*:

	All major technology areas have at least one backup option available at system acquisition commitment without any loss of fielded margin or demonstrated operational effectiveness characteristics (i.e., backup has also demonstrated reliability/dependability and responsiveness).
	All major technology areas have at least one backup option available at system acquisition commitment with only losses in fielded margin, but without any loss of demonstrated operational effectiveness characteristics (i.e., backups have also demonstrated reliability/dependability and responsiveness).
	More than fifty percent (50%) of the major technology areas have at least one backup option available at system acquisition commitment without any loss of fielded margin or operational effectiveness characteristics (i.e., backups have also demonstrated reliability/dependability and responsiveness), and the remaining technology areas only have loss of fielded margin.
	Only a few major technology areas have at least one backup option available at system acquisition commitment without any loss of fielded margin or operational effectiveness characteristics (i.e., backups have also demonstrated reliability/dependability and responsiveness), and the remaining technology areas only have loss of fielded margin.
	(STS) No major technology area backup options are available at system acquisition commitment.
	Current definition of concept insufficient to determine or outside programmatic boundaries.

Programmatics
Part 1.2B—<u>Technology</u> Research & Development Phase

The numbered assessment questions in Part 1.2B have been developed by the HRST Operations Assessment Team to provide the Assessment Team additional insight to programmatic considerations of the concept, particularly as they relate to specific technology research & development factors. As with the Operational Effectiveness parameters referred to by their "DF" designation in the first eighteen (18) questions (Part 1.1), and the six Program Acquisition Assessments (Part 1.2A), these questions cross-reference <u>programmatic factors</u> in the *Design Guide*'s "Program Considerations" section, and are designated as "(*#X-R&D*)"

25. Technology R&D—Time required to establish infrastructure (schedule of technology R&D phase) (*#3-R&D*):

	Infrastructure already exists without any upgrades required to do the technology R&D identified.
	Infrastructure already exists, but, some minor upgrades are required to accommodate the technology R&D identified. Upgrades (i.e., the funding, build and test cycle) can be accomplished in parallel with the design/build schedule of the test article, i.e., is not in the schedule critical path.
	Infrastructure already exists for development testing with minor upgrades required; but, the manufacturing & tooling infrastructure are not existing without major upgrades (basic manufacturing plant facility exists) and can be established in less than one year.
	Only the basic manufacturing (plant facility), the test article, and also the developmental testing infrastructure exist. Major upgrades are required for both the manufacturing and tooling and at the test facility, but, they can be established in less than two years.
	Infrastructure does not exist for either the major article testing or the manufacturing & tooling for the new test article. Acquisition and the establishment of these infrastructure elements will require in five or more years.
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

26. Technology R&D—Number of technologies considered high risk/difficult to achieve that are required to be developed and demonstrated (*#6-R&D*):

	No technologies considered high risk/difficult to achieve required. However, large subscale and full-scale demonstrations are required. (i.e., all enabling technologies are at TRL-4 or above).
	Only one technology considered high risk/difficult to achieve is required. (e.g., new material of which technology application feasibility has not been demonstrated). All other enabling technologies have been developed and demonstrated (i.e., technology readiness level-TRL-6 or above).
	Two to three technologies considered high risk/difficult to achieve are required (i.e., technology feasibility has not been demonstrated). All other enabling technologies have been developed and demonstrated (i.e., technology readiness level-TRL-6 or above).
	Five or less technologies considered high risk/difficult to achieve are required (i.e., technology feasibility has not been demonstrated). All other enabling technologies have been developed and demonstrated (i.e., technology readiness level-TRL-6 or above).
	Many technologies considered high risk/difficult to achieve are required (i.e., technology feasibility has not been demonstrated). Some other enabling technologies have been developed and demonstrated (i.e., technology readiness level-TRL-6 or above).
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

27. Technology R&D—Number of full-scale ground or flight demonstrations required (*#8-R&D*), (#9-R&D):

	All technologies are at TRL-6 or above (do not require additional full-scale ground or flight tests) and satisfy the Program Acquisition Criteria (Part 1.2A).
	All technologies are at TRL-6 or above, except one that requires flight test demonstration at full-scale to satisfy the Program Acquisition Criteria (Part 1.2A).
	All technologies are at TRL-6 or above, except one that requires both a full-scale ground and flight test program to satisfy the Program Acquisition Criteria (Part 1.2A).
	The concept architecture requires two to three full-scale technology area ground and flight test programs to satisfy the Program Acquisition Criteria (Part 1.2A).
	The concept architecture requires five or more full-scale ground test programs and at least one flight test program to satisfy the Program Acquisition Criteria (Part 1.2A).
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

28. Technology R&D—Degree of Difficulty to reach test in like environment (flight or ground) (i.e., technology readiness level is TRL-6); (#9-R&D), (*#13-R&D*), (#14-R&D), (*#17-R&D*),

	For the system being assessed, all basic principles have been observed and reported. All technologies and/or applications have been formulated. All necessary experimental proofs of concept are completed. All necessary, analogous hardware/software/database items exist. (i.e., technology readiness level is TRL-5). Demonstration in like environment still required. Time is estimated to take about **one to two (1-2) years**. (*Very low degree of difficulty*)
	For the system being assessed, all basic principles have been observed and reported. All technologies and/or applications have been formulated. All necessary experimental proofs-of-concept are completed. However, some analogous hardware/software/database items do not exist. (TRL-3,4). Time is estimated at about **two-four (2-4) years**. (*Moderate degree of difficulty*).
	For the system being assessed, all basic principles have been observed and reported. All technologies and/or applications have been formulated. However, necessary experimental proofs-of-concept are necessary and some analogous hardware/software/database items do not exist. (TRL-2,3). Time estimated **up to six (6) years.** (*High degree of difficulty*).
	For the system being assessed, all basic principles have been observed and reported. However, one or more technologies and/or applications have not been formulated. In addition, a few experimental proofs-of-concept are necessary and some analogous hardware/software/database items do not exist. (TRL-1,2). Time is estimated at **more six to ten (6-10) years.** (*Very high degree of difficulty*).
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

29. Technology R&D—Number of operational effectiveness attributes previously demonstrated (eight major attributes as related to design features in *Design Guide*) (*#10-R&D*):

	All operational effectiveness attributes (affordable, dependable, responsive, safe and environmentally compatible with public support) have been demonstrated (acquisition cost, schedule and recurring cost have no risk)
	All high priority operational effectiveness attributes have been demonstrated.
	Affordable (low acquisition & recurring), dependable and responsive attributes have been demonstrated.
	No operational effectiveness attributes (affordable, dependable, responsive, safe and environmentally compatible with public support) have been demonstrated.
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

30. Technology R&D—Number of applications beyond space transportation (*#12-R&D*):

	Greater than ten applications identified or highly visible from the new technology R&D required.
	Five to ten applications identified or highly visible from the new technology R&D required.
	Two to five applications identified or highly visible from the new technology R&D required.
	At least one application identified or highly visible from the new technology R&D required.
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

31. Technology R&D—Number of new facilities required that cost over $2M (*#15-R&D*); Cost to reach TRL-6 (#17-R&D); Total annual funding by item at peak dollar requirements (*#18-R&D*):

	There are no new facilities required that cost over $2M and the cost to reach TRL-6 is estimated at less than two hundred million dollars per year ($200M/yr) exclusive of large scale flight demonstration vehicles.
	There are no new facilities required that cost over $2M and the cost to reach TRL-6 is estimated at less than three hundred million dollars per year ($300M/yr) exclusive of large scale flight demonstration vehicles.
	One new facility is required that cost over $2M and the cost to reach TRL-6 is estimated at less than three hundred million dollars per year ($300M/yr) exclusive of large scale flight demonstration vehicles.
	One new facility is required that cost over $2M and the cost to reach TRL-6 is estimated at less than three hundred million dollars per year ($300M/yr) exclusive of large scale flight demonstration vehicles.
	(STS) Current definition of concept insufficient to determine or outside programmatic boundaries.

HRST Architectual Assessment Form
Design Feature Weighting

<u>HRST Major Design Areas   Relative Weight</u>

1. <u>*Overall*</u> *propulsion* <u>*packaging*</u> architecture.
   DF#6 - Number of different propulsion systems 496
2. <u>Main</u> propulsion <u>packaging</u> architecture.
   DF#26 - Number of engines 335
3. <u>Main</u> propulsion operating <u>dynamic events</u> & operating <u>modes</u> excluding start-up & final shutdown (e.g., staging, mixture ratio changing, throttling, mode changes like low-speed-to-high-speed system.
   DF#15 - Number of active components required to function including flight operations 412
4. Space Transportation System <u>*material selection.*</u>
   DF#23 - Number of confined spaces on vehicle 355
5. <u>*Structural interface*</u> architecture (number of stages and design-to interfaces).
   DF#7 - Number of unique stages (flight and ground) 493
   DF#30 - Number of element-to-element interfaces requiring engineering control (294)
6. Conceptual approach for <u>*reliability & dependability.*</u>
   DF#10 - Number of components with demonstrated high reliability 458
   DF#16 - Technology readiness levels (406)
7. Concept for <u>*system/mission safety & reliability*</u> (Crit 1 = loss of life/vehicle, Crit 2 = loss of mission).
   DF#25 - Number of propulsion sub-systems with fault tolerance 341
   DF#29 - Number of criticality 1 failure modes (320)
8. Transportation system <u>*vehicle complexity & safety dynamics.*</u>
   DF#12 - Number of active systems required to maintain a safe vehicle 439
   DF#15 - Number of active components required to function including flight operations (412)
   DF#19 - Number of systems requiring monitoring due to hazards (390)
   DF#33 - Percent of propulsion sub-systems monitored to change from hazard to safe (279)
   DF#39 - Number of active engine systems required to function (220)
9. Space transportation <u>system complexity</u>.
   DF#8 - Number of active ground systems required for servicing 464
   DF#20 - Number of parts (different, backup, complex) (370)
   DF#37 - Number of manufacturing, test and operations facilities (249)

10. Space transportation *maintainability* (on-line operation, not depot-level repair).
    DF#32 - Number of physically difficult-to-access areas 291

11. Fluid selection.
    DF#1 - Number of toxic fluids 597

12. Number of *different fluids* & flight vehicle-to-ground *interfaces.*
    DF#8 - Number of active ground systems required for servicing 464
    DF#17 - Number of different fluids in system (398)

13. Number of *different gases* & flight vehicle-to-ground *interfaces*.
    DF#9 - Number of purges required (flight and ground) 463
    DF#17 - Number of different fluids in system (398)

14. Ground *electrical power requirements* for turnaround.
    DF#8 - Number of active ground systems required for servicing 464
    DF#38 - Number of ground-power systems (234)

15. *Vehicle Health Management (VHM) capability.* (i.e., for all on-board systems including passive ones, such as thermal protection & structures).
    DF#3 - Number of systems with BIT BITE 521
    DF#13 - Percent of propulsion system automated (420)
    DF#14 - Number of hands-on activities required (416)
    DF# 22 - Number of checkouts required (360)
    DF#24 - Number of inspection points (346)

16. Concept for *controlling fluid/gas leakage* in the transportation system architectural design.
    DF#11 - Number of potential leakage connection sources 443

17. Environmental control.
    DF#4 - Number of confined spaces on vehicle 501

18. *Fielded* transportation system *margin* (i.e., for all on-board systems including passive ones, such as thermal protection & structures).
    DF#2 - System margin 526
    DF#18 - Mass fraction (395)
    DF#27 - Average Isp on reference trajectory (331)
    DF#40 - Margin, mass fraction (209)

HRST Architectual Assessment Form
Design Feature Weighting Summary

HRST Major Design Areas (Design Feature Alpha-Numeric) QFD Score - %

A. 11. Fluid selection.
DF#1 - Number of toxic fluids . . . . 597 -100
B. 18. Fielded transportation system margin.
DF#2 - System margin . . . . 526 - 88
C. 15. Vehicle Health Management (VHM) capability.
DF#3 - Number of systems with BIT BITE . . . . 521 - 87
D. 17. Environmental control.
DF#4 - Number of confined spaces on vehicle . . . . 501 - 84
E. 1. Overall propulsion packaging architecture.
DF#6 - Number of different propulsion systems . . . . 496 - 83
F. 5. Structural interface architecture (# of stages & design-to interfaces).
DF#7 - Number of unique stages (flight and ground) . . . . . 493 - 83
G. 9. Space transportation system complexity.
DF#8 - Number of active ground systems required for servicing 464 - 78
H. 12. Number of different fluids & flight vehicle-to-ground interfaces.
DF#8 - Number of active ground systems required for servicing . 464 - 78
I. 14. Ground electrical power requirements for turnaround.
DF#8 - Number of active ground systems required for servicing . 464 - 78
J. 13. Number of different gases & flight vehicle-to-ground interfaces.
DF#9 - Number of purges required (flight and ground) . . . . . . 463 - 78
K. 6. Conceptual approach for reliability & dependability.
DF#10 - # of components with demonstrated high reliability 458 - 77
L. 16. Concept for controlling fluid/gas leakage in transp. sys. arch. design.
DF#11 - Number of potential leakage connection sources . . . . 443 - 74
M 8. Transportation system vehicle complexity & safety dynamics.
DF#12 - # of active systems required to maintain a safe vehicle . 439 - 74
N. 3. Main propulsion operating dynamic events & operating modes excluding start-up & final shutdown.
DF#15 - # of active comps. reqd. to func. including flight opers . . 412 - 69
O. 4. Space Transportation System material selection.
DF#23 - Number of confined spaces on vehicle . . . . 355 - 59
P. 7. Concept for system/mission safety & reliability
DF#25 - Number of propulsion sub-systems with fault tolerance . 341 - 57
Q. 2. Main propulsion packaging architecture.
DF#26 - Number of engines . . . . 335 - 56
R. 10. Space transportation maintainability (on-line operation)
DF#32 - Number of physically difficult-to-access areas . . . . . . 291 - 49

SUMMARY OF ASSESSMENT CATEGORIES

ASSESSMENT CATEGORY	RELATIVE WEIGHT
1. *Overall propulsion packaging* architecture.	496
2. Main propulsion packaging architecture.	335
3. Main propulsion operating dynamic events & operating modes excluding start-up & final shutdown	412
4. Space Transportation System *material selection.*	355
5 *Structural interface* architecture (number of stages and design-to interfaces).	493
6 Conceptual approach for *reliability & dependability.*	458
7. Concept for *system/mission safety & reliability*	341
8. Transportation system *vehicle complexity & safety dynamics*.	439
9. Space transportation system complexity.	464
10. Space transportation *maintainability*	291
11. Fluid selection.	597
12. Number of *different fluids* & flight vehicle-to-ground *interfaces.*	464
13. Number of *different gases* & flight vehicle-to-ground *interfaces*.	463
14. Ground *electrical power requirements* for turnaround.	464
15. Vehicle Health Management (VHM) capability.	521
16. Concept for *controlling fluid/gas leakage* in the transportation system architectural design.	443
17. Environmental control.	501

18. *Fielded* transportation system *margin.* . . . .
526

The number at the right-hand side of each category is a relative-weight indicator
described in the supplement.

HRST ARCHITECTURAL ASSESSMENT FORM

ASSESSMENT CATEGORY WEIGHT SUMMARY

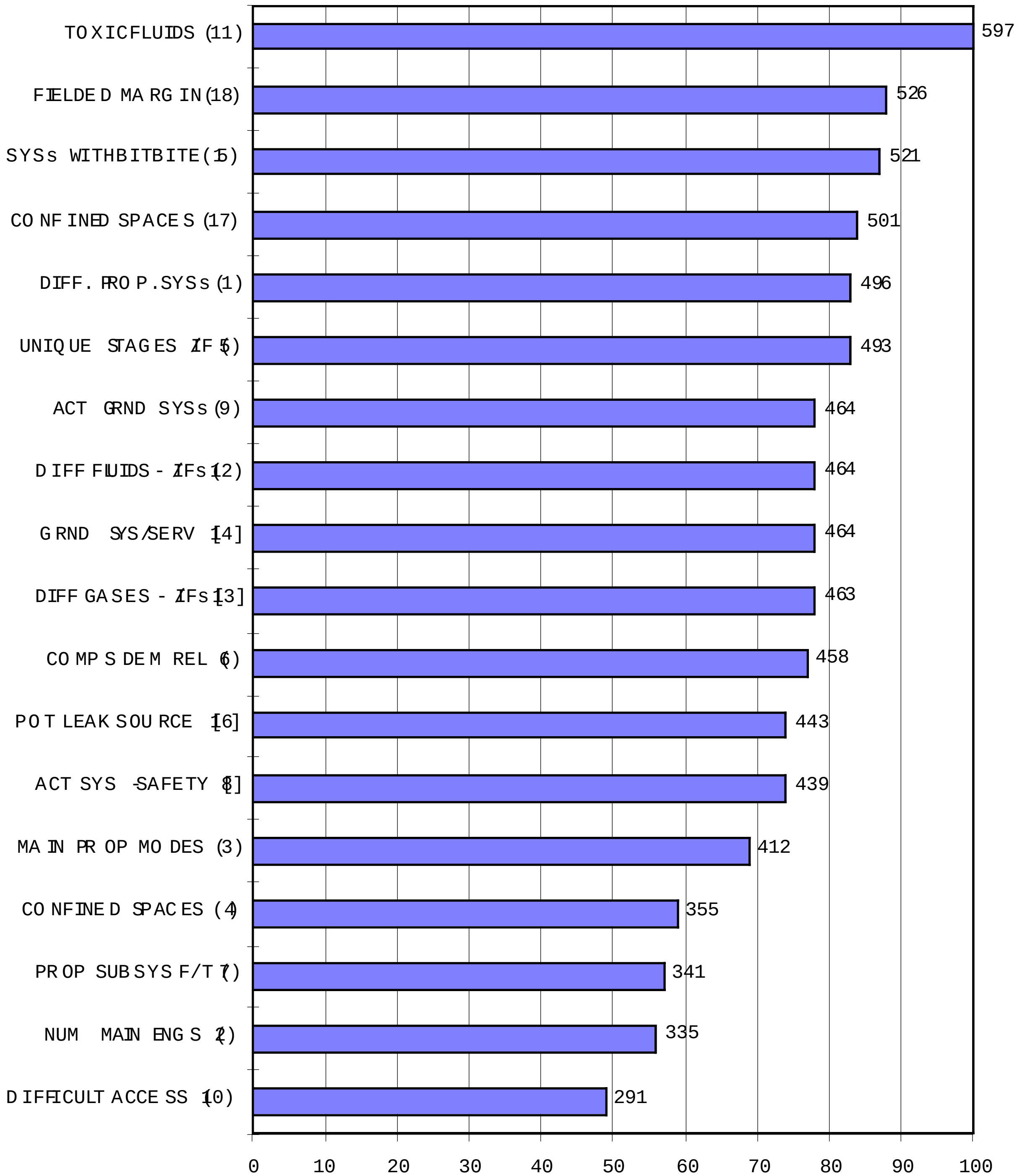


Table of AAT Score Values

Question	Top box Score	2nd box	3rd box	4th box	5th box	6th box	7th box	8th box	Bottom box
1	10	7	5	3					1
2	10	9	8	7	6	5	4	2	1
3	10	8	6	4	2				1
4	10	7	5	3					1
5	10	7	5	3					1
6	10	7	5	3					1
7	10	7	5	3					1
8	10	7	5	3					1
9	10	7	5	3					1
10	10	8	6	4	2				1
11	10	7	5	3					1
12	10	8	6	4	2				1
13	10	8	6	4	2				1
14	10	7	5	3					1
15	10	8	6	4	2				1
16	10	7	5	3					1
17	10	7	5	3					1
18	10	7	4						1
19	10	8	6	4	2	1			1
20	10	8	6	4	2				1
21	10	8	6	4	2				1
22	10	7	5	3					1
23	10	8	6	4	2				1
24	10	8	6	4	2				1
25	10	8	6	4	2				1
26	10	8	6	4	2				1
27	10	8	6	4	2				1
28	10	7	5	3					1
29	10	7	5	3					1
30	10	7	5	3					1
31	10	7	5	3					1

OPS HITF TEAM CONCEPT ASSESSMENT DETAILED RESULTS (AAT)

Access-to-Space Reference Score Summary	
Operational Effectiveness	49
Acquisition Programmatic	32
R&D Programmatic	46

ATS-Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	49
2	335.0	4.2	4	
3	412.0	5.1	8	
4	355.0	4.4	5	
5	493.0	6.1	7	
6	458.0	5.7	5	
7	341.0	4.2	5	
8	439.0	5.4	3	
9	464.0	5.8	5	
10	291.0	3.6	4	
11	597.0	7.4	5	
12	464.0	5.8	4	
13	463.0	5.7	8	
14	464.0	5.8	5	
15	521.0	6.5	4	
16	443.0	5.5	5	
17	501.0	6.2	3	
18	526.0	6.5	4	
Sum	8063.0			

ATS–Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	32
20	9.0	20.0	6	
21	7.0	15.6	8	
22	7.0	15.6	1	
23	6.0	13.3	2	
24	5.0	11.1	1	
Sum	45.0			

ATS – Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	6	46
26	6.0	16.2	6	
27	6.0	16.2	2	
28	5.0	13.5	5	
29	5.0	13.5	3	
30	4.0	10.8	5	
31	4.0	10.8	10	
Sum	37.0			

STS (Shuttle) Reference Score Summary	
Operational Effectiveness	34
Acquisition Programmatic	36
R&D Programmatic	9

STS--Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	34
2	335.0	4.2	8	
3	412.0	5.1	6	
4	355.0	4.4	3	
5	493.0	6.1	3	
6	458.0	5.7	3	
7	341.0	4.2	3	
8	439.0	5.4	3	
9	464.0	5.8	3	
10	291.0	3.6	2	
11	597.0	7.4	3	
12	464.0	5.8	2	
13	463.0	5.7	2	
14	464.0	5.8	5	
15	521.0	6.5	2	
16	443.0	5.5	3	
17	501.0	6.2	3	
18	526.0	6.5	4	
Sum	8063.0			

STS--Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	6	36
20	9.0	20.0	6	
21	7.0	15.6	2	
22	7.0	15.6	1	
23	6.0	13.3	2	
24	5.0	11.1	2	
Sum	45.0			

STS--Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	1	9
26	6.0	16.2	1	
27	6.0	16.2	1	
28	5.0	13.5	1	
29	5.0	13.5	1	
30	4.0	10.8	1	
31	4.0	10.8	1	
Sum	37.0			

Marquardt HITF-Score Summary	
Operational Effectiveness	54
Acquisition Programmatic	27
R&D Programmatic	29

Marquardt HITF-Score-Operational Effectiveness Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	54
2	335.0	4.2	2	
3	412.0	5.1	2	
4	355.0	4.4	5	
5	493.0	6.1	10	
6	458.0	5.7	5	
7	341.0	4.2	7	
8	439.0	5.4	4	
9	464.0	5.8	5	
10	291.0	3.6	8	
11	597.0	7.4	5	
12	464.0	5.8	5	
13	463.0	5.7	8	
14	464.0	5.8	7	
15	521.0	6.5	6	
16	443.0	5.5	5	
17	501.0	6.2	4	
18	526.0	6.5	4	
Sum	8063.0			

Marquardt HITF-Score-Acquisition Programmatics Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	27
20	9.0	20.0	2	
21	7.0	15.6	6	
22	7.0	15.6	1	
23	6.0	13.3	2	
24	5.0	11.1	6	
Sum	45.0			

Marquardt HITF-Score–Techn. R&D Programmatic Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	6	29
26	6.0	16.2	2	
27	6.0	16.2	2	
28	5.0	13.5	3	
29	5.0	13.5	3	
30	4.0	10.8	5	
31	4.0	10.8	3	
Sum	37.0			

ACRE-183 HIF-Score Summary	
Operational Effectiveness	52
Acquistion Programmatic	15
R&D Programmatic	50

ACRE-183 HIF-Score-Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	52
2	335.0	4.2	4	
3	412.0	5.1	8	
4	355.0	4.4	5	
5	493.0	6.1	7	
6	458.0	5.7	5	
7	341.0	4.2	5	
8	439.0	5.4	3	
9	464.0	5.8	5	
10	291.0	3.6	4	
11	597.0	7.4	5	
12	464.0	5.8	4	
13	463.0	5.7	8	
14	464.0	5.8	5	
15	521.0	6.5	4	
16	443.0	5.5	5	
17	501.0	6.2	4	
18	526.0	6.5	7	
Sum	8063.0			

ACRE-183 HIF-Score-Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	15
20	9.0	20.0	2	
21	7.0	15.6	2	
22	7.0	15.6	1	
23	6.0	13.3	1	
24	5.0	11.1	2	
Sum	45.0			

ACRE-183 HIF-Score-Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	8	50
26	6.0	16.2	6	
27	6.0	16.2	2	
28	5.0	13.5	5	
29	5.0	13.5	3	
30	4.0	10.8	5	
31	4.0	10.8	10	
Sum	37.0			

Hyperion HITF-Score Summary	
Operational Effectiveness	51
Acquisition Programmatic	26
R&D Programmatic	27

Hyperion Self Score--Operational Effectiveness Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	51
2	335.0	4.2	6	
3	412.0	5.1	2	
4	355.0	4.4	5	
5	493.0	6.1	5	
6	458.0	5.7	5	
7	341.0	4.2	7	
8	439.0	5.4	3	
9	464.0	5.8	5	
10	291.0	3.6	6	
11	597.0	7.4	5	
12	464.0	5.8	4	
13	463.0	5.7	4	
14	464.0	5.8	5	
15	521.0	6.5	6	
16	443.0	5.5	5	
17	501.0	6.2	3	
18	526.0	6.5	10	
Sum	8063.0			

HyperionHITF-Score-Acquisition Programmatics Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	26
20	9.0	20.0	2	
21	7.0	15.6	8	
22	7.0	15.6	1	
23	6.0	13.3	1	
24	5.0	11.1	4	
Sum	45.0			

Hyperion HITF-Score--Technology R&D Programmatic Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	6	27
26	6.0	16.2	2	
27	6.0	16.2	2	
28	5.0	13.5	3	
29	5.0	13.5	3	
30	4.0	10.8	5	
31	4.0	10.8	1	
Sum	37.0			

Argus HITF-Score Summary	
Operational Effectiveness	59
Acquisition Programmatic	23
R&D Programmatic	29

Argus HITF-Operational Effectiveness Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	59
2	335.0	4.2	9	
3	412.0	5.1	2	
4	355.0	4.4	5	
5	493.0	6.1	7	
6	458.0	5.7	5	
7	341.0	4.2	5	
8	439.0	5.4	3	
9	464.0	5.8	7	
10	291.0	3.6	8	
11	597.0	7.4	5	
12	464.0	5.8	5	
13	463.0	5.7	8	
14	464.0	5.8	3	
15	521.0	6.5	8	
16	443.0	5.5	7	
17	501.0	6.2	4	
18	526.0	6.5	10	
Sum	8063.0			

Argus HITF-Score-Acquisition Programmatics Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	23
20	9.0	20.0	2	
21	7.0	15.6	6	
22	7.0	15.6	1	
23	6.0	13.3	1	
24	5.0	11.1	4	
Sum	45.0			

Argus HITF-Score-Technology R&D Programmatic Assessment				
Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	4	29
26	6.0	16.2	4	
27	6.0	16.2	2	
28	5.0	13.5	5	
29	5.0	13.5	3	
30	4.0	10.8	7	
31	4.0	10.8	1	
Sum	37.0			

TSTO HITF-Score Summary	
Operational Effectiveness	44
Acquisition Programmatic	35
R&D Programmatic	52

TSTO HITF-Score – Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	5	44
2	335.0	4.2	2	
3	412.0	5.1	6	
4	355.0	4.4	5	
5	493.0	6.1	3	
6	458.0	5.7	5	
7	341.0	4.2	4	
8	439.0	5.4	3	
9	464.0	5.8	3	
10	291.0	3.6	2	
11	597.0	7.4	5	
12	464.0	5.8	3	
13	463.0	5.7	2	
14	464.0	5.8	5	
15	521.0	6.5	4	
16	443.0	5.5	5	
17	501.0	6.2	5	
18	526.0	6.5	10	
Sum	8063.0			

TSTO HITF-Score – Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	35
20	9.0	20.0	6	
21	7.0	15.6	6	
22	7.0	15.6	1	
23	6.0	13.3	4	
24	5.0	11.1	4	
Sum	45.0			

TSTO HITF-Score – Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	6	52
26	6.0	16.2	10	
27	6.0	16.2	2	
28	5.0	13.5	5	
29	5.0	13.5	3	
30	4.0	10.8	5	
31	4.0	10.8	10	
Sum	37.0			

NDV (LaRC) HITF-Score Summary	
Operational Effectiveness	47.9
Acquisition Programmatic	17.1
R&D Programmatic	19.5

NDV (LaRC) HITF Score--Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	6	48
2	335.0	4.2	6	
3	412.0	5.1	2	
4	355.0	4.4	5	
5	493.0	6.1	7	
6	458.0	5.7	5	
7	341.0	4.2	5	
8	439.0	5.4	3	
9	464.0	5.8	5	
10	291.0	3.6	4	
11	597.0	7.4	5	
12	464.0	5.8	4	
13	463.0	5.7	8	
14	464.0	5.8	5	
15	521.0	6.5	4	
16	443.0	5.5	5	
17	501.0	6.2	3	
18	526.0	6.5	4	
Sum	8063.0			

NDV (LaRC) Self Score--Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	17
20	9.0	20.0	1	
21	7.0	15.6	4	
22	7.0	15.6	1	
23	6.0	13.3	2	
24	5.0	11.1	2	
Sum	45.0			

NDV (LaRC) Self Score--Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	2	19
26	6.0	16.2	2	
27	6.0	16.2	2	
28	5.0	13.5	3	
29	5.0	13.5	3	
30	4.0	10.8	3	
31	4.0	10.8	1	
Sum	37.0			

BNA HITF-Score Summary	
Operational Effectiveness	48
Acquisition Programmatic	18
R&D Programmatic	23

BNA HITF-Score – Operational Effectiveness Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
1	496.0	6.2	6	48
2	335.0	4.2	2	
3	412.0	5.1	2	
4	355.0	4.4	5	
5	493.0	6.1	7	
6	458.0	5.7	5	
7	341.0	4.2	4	
8	439.0	5.4	3	
9	464.0	5.8	6	
10	291.0	3.6	4	
11	597.0	7.4	5	
12	464.0	5.8	4	
13	463.0	5.7	8	
14	464.0	5.8	5	
15	521.0	6.5	4	
16	443.0	5.5	5	
17	501.0	6.2	3	
18	526.0	6.5	7	
Sum	8063.0			

BNA HITF-Score – Acquisition Programmatics Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
19	11.0	24.4	1	18
20	9.0	20.0	1	
21	7.0	15.6	4	
22	7.0	15.6	1	
23	6.0	13.3	1	
24	5.0	11.1	4	
Sum	45.0			

BNA HITF-Score – Technology R&D Programmatic Assessment

Question	Weight	Normalized Weight	Concept Entry (1 to 10)	Final Score
25	7.0	18.9	4	23
26	6.0	16.2	2	
27	6.0	16.2	2	
28	5.0	13.5	3	
29	5.0	13.5	3	
30	4.0	10.8	1	
31	4.0	10.8	1	
Sum	37.0			

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APPENDIX F - Analysis using Reliability Maintainability Analysis Tool (RMAT)

(W. Douglas Morris, Nancy H. White, Langley Research Center)

PURPOSE:

To develop estimates of the maintenance burden, maintenance processing time and staffing requirements based on the HRST concept’s design, technology selection and support concept. These results are traceable to historical support requirements of similar systems on the Shuttle and aircraft. This is not intended as a complete standalone comparison of the concepts, instead the information developed is intended to aid in the assessment process and to provide quantifiable results to be used in conjunction with other HRST studies.

OVERVIEW:

The R&M characteristics of a concept are a quantifiable measure of its operability. As a part of the HRST study Langley developed computer models to define these R&M parameters associated with several representative study concepts provided by team members. This work uses the Reliability Maintainability Analysis Tool (RMAT) to generate system/subsystems reliability and maintainability (R&M) values for the candidate vehicle concepts. This tool was used to develop a reference set of R&M parameters for each concept from which support parameters such as maintenance burden, processing times, staffing and fleet size were derived. These parameters are intended to provide guidance in the choice of characteristic values for simulation studies of the concept's support scenario.

RMAT DESCRIPTION:

The RMAT is a top level analysis tool developed by the Langley Research Center's (LaRC) Vehicle Analysis Branch (VAB) as part of an analysis tool set described in references 1-4. The primary purpose of this analysis tool is to aid in the definition of R&M parameters for launch vehicle concepts. It is based on comparability to aircraft and Shuttle R&M characteristics for similar systems and is driven by the vehicle description in terms of subsystem weights, vehicle dimensions and other system specific variables. These descriptors are used as independent parameters with a set of parametric equations based on aircraft systems to define the R&M values for the new concept. The descriptors can also be integrated with a set of parameters derived from the Shuttle program to estimate the vehicle level R&M characteristics based on comparability to those systems. The R&M results can in turn be used to estimate, at top level, the support requirements of advanced concepts.

ANALYSIS METHOD:

The analysis process is based on defining support for these concepts from the predicted number of maintenance actions required after each mission, the personnel and time required for repair, and the amount of preventive maintenance used to ensure reliable operation. The goals expressed in the CAN were used to define a set of constraints that the concepts had to achieve. They were, a seven day or less turnaround for each vehicle, a mission length of at least 48 hours, and supporting a 200 flight per year mission model with a fleet of vehicles requiring 250 ‘direct charge’ personnel or less. Because of the limited time available neither vehicle life, engine life, nor maintenance overhauls were addressed at this time.

The Shuttle orbiter is included in the study for the purpose of reference. A set of factors were then developed for each subsystem to adjust the R&M values for HRST concepts based on design, technology and processing differences with the Shuttle Orbiter reference.

All HRST concepts were subject to the following assumptions:

- All systems are assumed capable of performing the mission.
- Comparability to Shuttle systems was chosen for all subsystems except the Landing Gear, Battery, Electrical, Actuators, Avionics, and Environmental Control, which were based on aircraft.
- All systems were assumed to have an IOC of 2010. This assumes that the technologies associated with each subsystem will exhibit improvements in MTBM equivalent to that observed for the reference technologies of the databases used in the RMAT model. These rates vary by subsystems and the annual values used for this study are shown in table 1.

Table 1. Technology Growth Factors	%
Wing Group	8.20
Tail Group	8.20
Body Group	8.20
Tanks-LOX	8.20
Tanks-LH2	8.20
IEP-Tiles	8.20
IEP-TCS	8.20
IEP-PVD	8.20
Landing Gear	3.30
Propulsion-Main Engines	1.10
Propulsion-MPS	1.10
Propulsion-RCS	1.10
Propulsion-OMS	1.10
Power-Battery	5.60
Power-Fuel Cell	5.60
Electrical	0.00
Aero Actuators	5.60
Aggregated Avionics	22.00
Environmental Control	0.62

• All systems assume a 15% indirect labor burden for the technicians performing the maintenance and processing. This value is typical of that observed in military support and represents an improvement over the 30% value assumed for Shuttle processing.

• All systems assume the amount of scheduled maintenance will be based on a percentage of the computed unscheduled maintenance for each concept. This percentage is predicted from a database of aircraft operations and was applied equally across all subsystems.

• A 7 day processing turnaround was used as a goal for each vehicle, minimum mission length of 48 hours, and a 200 flight per year mission model was assumed for the fleet based on the CAN requirements with a goal of no more than 250 ‘direct charge’ personnel.

• Phased (or depot) maintenance was not addressed in these initial studies.

The Process:

• Each concept was defined in the RMAT model.
• Comparability to either aircraft or Shuttle was selected for each subsystem.
• The factors developed to account for design (size, volume, area, number, etc.) and/or processing changes were entered.
• Each concept was analyzed based on the above assumptions.
    • Run at 200 flights/year to obtain vehicle processing support levels.
    • Adjust personnel numbers to reduce longer maintenance times to fit within the 7 day turnaround goal. (Assumes unlimited access to work on the systems.)
    • If results fit within the constraints, record results.
    • If not, determine a combination of MTBM’s and MH/OH characteristics for those systems which are maintenance drivers that allow the concept to meet the goals, and note what those requirements would be.
    • Record results.

CONCEPT DESCRIPTIONS:

The concepts were defined through a series of briefings and are summarized Appendix B.

RESULTS & DISCUSSION:

The results of this study are summarized in Figures 1-5 respectively for the ground processing maintenance burden, manpower, turnaround time, and corresponding fleet size. In all figures the Adjusted Shuttle Orbiter (only reusable elements, no SRB or ET) is included as if it were a SSTO for the purpose of comparison. The RMAT model has assumed an improvement in the reliability of the database technologies at the rates shown in table 1 for all concepts. (For those Shuttle subsystems for which there was no comparable aircraft subsystems rates were assumed based on related aircraft technologies e.g., Shuttle tanks used aircraft structural rates.) This assumption along with the assumption that the preventive maintenance requirements of future systems will be able to match that of today's aircraft reduces the Shuttle Orbiter's current maintenance burden from approximately 100,000 manhours of touch labor per flow to 21,800 manhours per flow. In order for the HRST concepts to meet the CAN requirements, it was necessary to make additional assumptions for improvements to the R&M characteristics of those subsystems that appeared to be maintenance drivers. The assumption was made that the maintenance manhours per maintenance action could be reduced by half for those systems based on Shuttle comparability and that the rate at which maintenance actions occur will be improved by an order of magnitude for the structural systems, MPS and main engines, and two orders for the TPS. These assumptions then represent R&M requirements to be achieved by the new technologies used on the HRST concepts.

In Figure 1, the left-hand column (1) for each concept illustrates the effect of normal technology growth (Table 1) and aircraft levels of scheduled maintenance on the total maintenance burden for each concept. (Note: The maintenance burden for the HRST concepts is larger than that for the Adjusted Shuttle Orbiter because this system's size reflects orbital flight capability. The Adjusted Shuttle Orbiter values represent only the reusable portions of the Space Transportation System.) Differences in burdens are due to the relative size differences for each subsystem, the differences in the types of subsystems on each concept, and differences in assumptions of comparability.

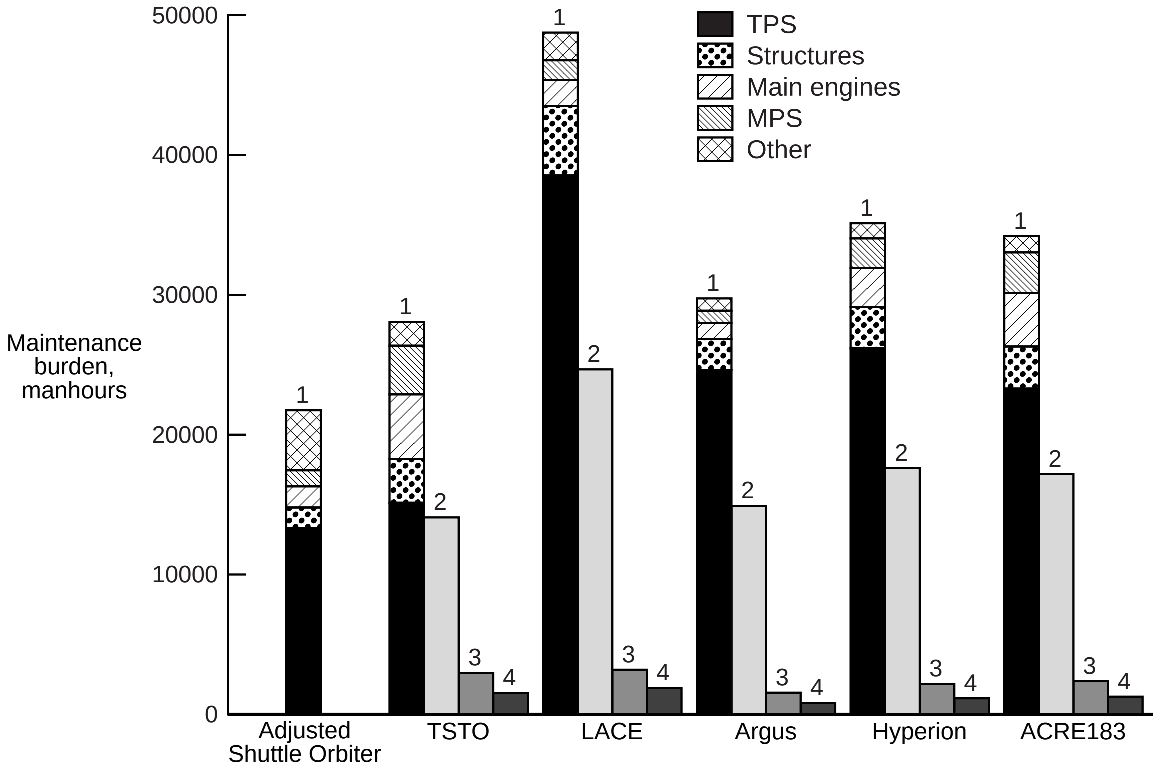

Figure 1

The top maintenance drivers are shown for each system. In all cases, the major driver was the TPS system, representing from 55 to 83 percent of the total burden. Structures, Main Engines, and MPS are generally the next major contributors, the order depending on the concept. The next column to the right (2), represents the reduced burden that would occur if the 50% maintenance reduction assumptions alone were made. The next column (3) represents the results if the assumption of order of magnitude improvements in reliability were made alone. Neither set of assumptions was sufficient to meet CAN requirements when applied individually. The right most column (4) for each concept shows the results when both sets of assumptions are incorporated. This reduced burden for each concept was then used for further analysis shown in figures 2-5.

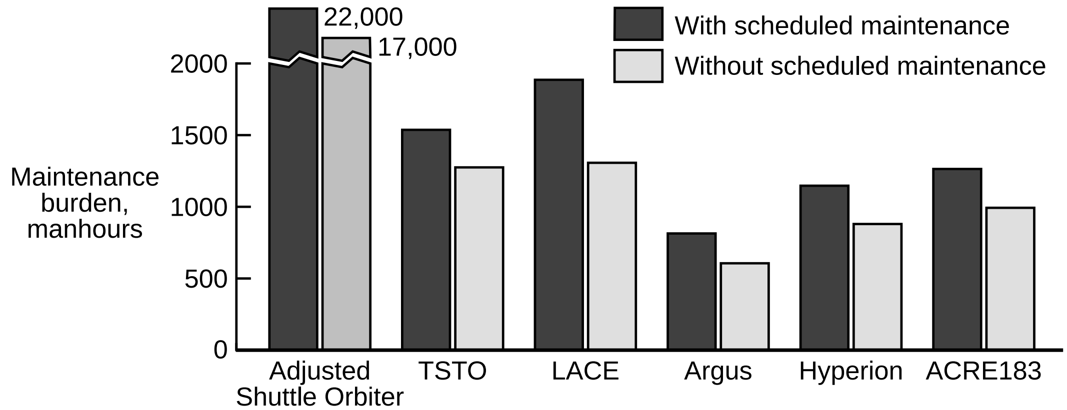

Figure 2

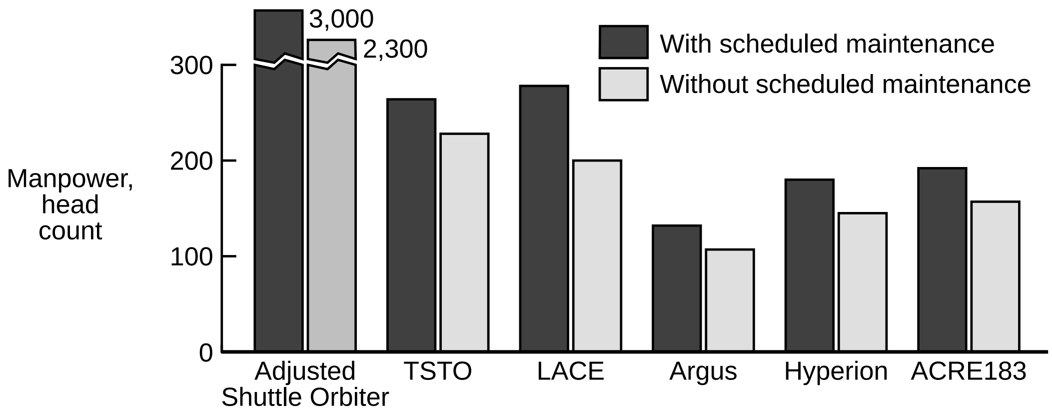

Figure 3

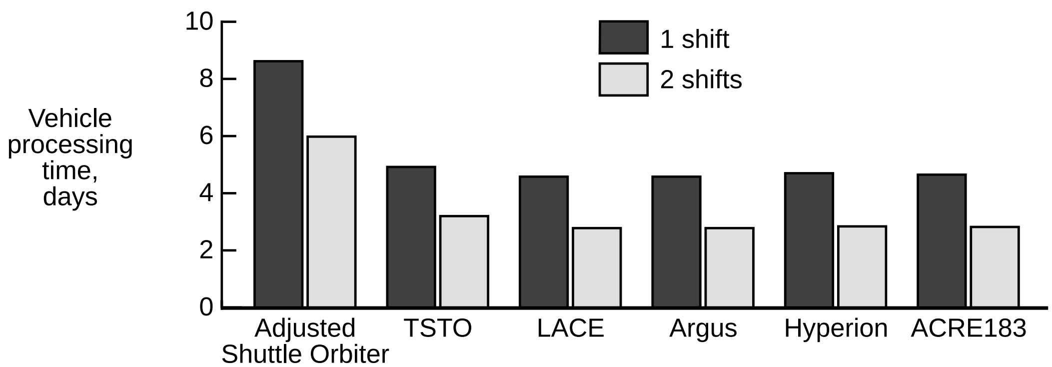

Figure 4

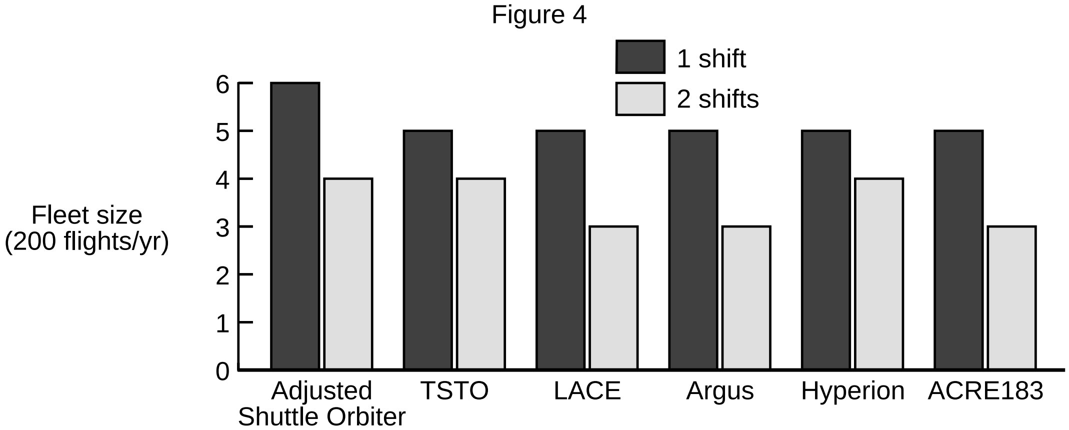

Figure 5

Two different maintenance concepts are illustrated (Figure 2) for working off the maintenance burden defined in column 4. The Shuttle maintenance concept performs preventive maintenance on each processing flow (with scheduled maintenance), while the aircraft concept performs phased maintenance only at periodic times after multiple flights (without scheduled maintenance). These effects are illustrated by the larger burden representing the Shuttle support concept, working off the scheduled hours on each flow. The smaller burden represents the per mission requirements when the phased or depot work is done only periodically as is typical of aircraft support. (Note: The burden for Argus does not include that for the launch assist support.)

The resulting manpower to work off the maintenance burden is illustrated in Figure 3. These results reflect staffing levels necessary to accommodate the indirect work, holidays, vacation and sick leave. Since it is assumed that the number of technicians that can work simultaneously on a system is not constrained, additional personnel are added to the systems that are maintenance drivers to reduce the processing time to that required by the CAN for a single vehicle turnaround (7 days total TAT, includes 48 hour mission). Not all systems require full use of this turn around time and thus those personnel are available to work other systems that are being processed concurrently. So there are some benefits from the economy of scale for fleet processing to support the 200 flights per year requirement. The manpower values represent a combination of the number of technicians required for productive labor, plus the additional techs required to meet the 7 day turnaround goal from the CAN on any single flight. These manpower results assume that technician crews are unique to each of the subsystems and cannot cross disciplines to work on similar subsystems. This is somewhat restrictive, but for comparison purposes between concepts provides relative staffing requirements. Actual staffing levels should be somewhat smaller than the results shown.

Figures 4 and 5 illustrate the processing times and fleet size only for the results when using the Shuttle maintenance concept. The vehicle processing times are shown in Figure 4 for both one and two shift work. Similar processing times were achieved by adding support personnel to fit to the allowable processing time available. This assumes a seven day turnaround for each vehicle that includes a 2 day mission, 1 day on the pad and a half day integration for the two stage concept. The 1 day of pad time is also assumed for horizontal takeoff vehicles for servicing prior to flight.

Figure 5 illustrates the corresponding fleet size for each concept. The differences for the study concepts are due to small differences in the processing times.

All concepts need more detailed studies that consider factors based on their specific technology choices and specifics of their processing requirements. These would provide better discriminators among the concepts. Although the assumptions made for improvement in system reliability and supportability were to meet the CAN requirements, they may not be that unrealistic to achieve. For Shuttle systems, many of today's maintenance actions result from the uncertainty associated with new systems. Experience in support will provide the confidence to reduce the problem reports (PR's) written against these systems. In addition, the relative high manhours required to support each maintenance action are in part due to gaining access to systems through a thermal barrier. The use of new attachment methods allowing non-destructive R&R may provide this reduction. Even with the 50% reduction assumed from Shuttle support levels, most MH/MA values are still 2 to 3 times greater than similar aircraft support levels. No assumptions were made to reduce crew sizes. Touch labor for both aircraft and Shuttle support were generally in the range of 1 to 2 technicians and this is not likely to show a significant reduction.

The differences in results illustrated here are due only to size, number of systems, and system requirements. Differences in technology choices are not reflected in these results. These differences need to be reflected, but require more time than currently available. The time available also limited the number of concepts that could be studied. The relative support requirements do however provide an indication of the staffing levels and the R&M characteristics necessary for these new technologies to achieve the HRST goals as defined in the CAN.

CONCLUSIONS:

The purpose of this analysis was to develop estimates of the maintenance burden; maintenance processing time and staffing requirements based on the HRST concept's design, technology selection and support concept. These results are provided for representative HRST concepts based on the support requirements of similar systems on the Shuttle and aircraft. The estimated improvements for these systems are based on HRST goals, not on analysis of individual technologies at this time. The results are not intended as a complete standalone comparison of the concepts, instead the information developed is intended to aid in the assessment process and to provide quantifiable results to be used in conjunction with other HRST studies.

REFERENCES:

1. Ebeling, C. E., "Parametric Estimation of R&M Parameters During the Conceptual Design of Space Vehicles." IEEE 1992 National Aerospace and Electronics Conference, Vol. 3, Univ. of Dayton, Dayton OH, pp. 955-959

2. Morris, W. D., N. H. White, W. T. Davis and C. E. Ebeling, "Defining Support Requirements During Conceptual Design of Reusable Launch Vehicles," Presented at the AIAA 1995 Space Programs and Technologies Conference, September 26-28, 1995, paper No. AIAA-95-3619.

3. Morris, W. D., N. H. White and C. E. Ebeling, "Analysis of Shuttle Orbiter Reliability and Maintainability Data for Conceptual Studies," Presented at the AIAA 1996 Space Programs and Technologies Conference, September 24-26, 1996, paper No. AIAA-96-4245.

4. Morris, W. D., N. H. White, W. T. Davis and C. E. Ebeling, "Estimating Logistics Support of Reusable Launch Vehicles During Conceptual Design," Presented at the 32nd Annual International Logistics Conference and Exposition, August 5-7, 1997, Orlando, Florida.

APPENDIX G - Hierarchical Analysis of Highly Reusable Space Transportation Architectures

(Richard W. Brown, Marshall Space Flight Center)

Objective:

The objective of this study was to evaluate candidate Highly Reusable Space Transportation (HRST) architectures to determine those that best fit NASA strategic plans. Results from the study will provide managers with an indication of which architectures should be considered for technology and vehicle development studies.

Method:

The basic methodology used in this study was the hierarchical analysis method, developed by Dr. Thomas L. Saaty. This method is used for decision analysis where a deterministic solution is not possible, and decisions are based on pair-wise comparisons of alternatives relative to the criteria that measure program success. Note that this method is a general-purpose decision analysis tool, and not a dedicated operations analysis tool. This method has four basic steps:

(1) <u>Determine the objective of the project and develop measures of success.</u> The objective is what the project is trying to do, and should be the first thing set in any project. Measures of success are slightly more complicated because there can be any number of levels of criteria for success. The objective must be analyzed to determine what are the key factors in meeting the objective. Then each of the factors is broken down into criteria that describe that factor's measures for success. Likewise, each of the criteria can be broken down into sub-criteria to as low as level required.

(2) <u>Evaluate the factors, criteria, and sub-criteria to determine those that are most important to the reaching the project objective.</u> A pair-wise comparison of preferences at each level and branch of the preference tree accomplishes this. For example each of the objective's factors would be compared against each other, with one factor rated as equal or n times better than the other. This would be accomplished for each criteria of a factor to determine which criteria are most important to that factor, and for each sub-criterion to determine its relative importance to its parent criteria. The result is a preference matrix for the project.

(3) <u>Determine the alternatives to be considered and a conduct a pair-wise comparison of alternatives for the lowest level sub-criteria of the project model.</u> In other words, you rate each of the alternatives against one another with respect each of the lowest level (i.e. no further breakdown) sub-criteria. This must be accomplished for each sub-criterion before the final results can be calculated.

(4) <u>Calculate resulting preference vector for the alternatives.</u> The result vector is calculated using the alternative ranking from the lowest level criteria and flowing upward to the project objective. At each level of the model, the preference matrix of the current level combines results from the previous level. This is continued though the factor level, one level below the objective. The final result is a matrix of alternative scores that sum to one.

For this study, steps two and four were computed using Expert Choice's "EC Pro" software package. While this package does have its faults, it does provided more flexibility in analyzing and displaying the results, then our "home brew" hierarchical analysis programs.

Approach:

The basic approach to hierarchical analysis, as note above, was used for the HRST study. The first step of that analysis was to determine the objective of the study and the factors and criteria to measure progress toward that objective. Since the purpose of the study was to choose the most promising candidates for further development, it was the obvious choice for the objective.
With the objective set, the next step is to determine measures of progress toward the objective. At this point two different sets of criteria were developed and with each developed as a separate model. The first model was based on the architecture survey that was sent to each developer. The second model consisted of a set of factors and criteria developed by Mr. John Mankins of NASA Headquarters.

<u>Survey Based Model</u>

The survey based model consisted of the 37 question, multiple-choice survey sent to each developer. A copy of this questionnaire may be found at the end of this Appendix. It includes the architectural section developed by Messrs. Edgar Zapata, Russel Rhodes, and Carey McCleskey, of KSC (questions 1 though 17), and the infrastructure questions (18 – 37) developed by Mr. R. W. Brown, of MSFC.

NOTE: Two Sub-Appendices, G-A and G-B, to Appendix G contain information pertinent to the discussions herein. Due to software incompatibilities, these were not available for inclusion in electronic format. Hardcopies of Sub-Appendices G-A and G-B are available upon request. Please contact the author of Appendix G, Dick Brown, at 205-544-6416.

Each of the questions on the survey was assigned to one of the factors of the objective. These factors included propulsion, structures, safety and reliability, ground processing, infrastructure, manufacturing, launch operations, and mission operations. In Sub-Appendix G-A, on page G-A-1 the reader will find a breakdown of the objective into the major factors (just noted) and further down into the criteria for each of the factors. On the far right of the sheet are the concepts that were evaluated. Note that not all of the developers responded to the survey.

The sheets (G-A-2 and G-A-3) after the project breakdown contain the definitions of the abbreviations used in the model. Note that the definitions that represent individual questions on the survey (e.g. Access) start with the question number from the survey form.

With the objective and factors decided, the next step was to develop a preference vector through pair-wise comparisons. As illustrated in figure one, a pair-wise comparison requires that each member of a group be compared with all other members of that group. The value entered is the relative value of the two criteria, thus criteria one is twice as important as criteria two. Note that the group being analyzed can be the factors of the objective, criteria of each factor, or sub-criteria of each criterion. For the preference matrix to be calculated, a pair-wise comparison of each factor, criteria, or sub-criteria of the model must be complete for any object that has sub-objects.

Factor A	**Criteria 2**	**Criteria 3**	**Criteria 4**	**Criteria 5**
Criteria 1	2	3	2	1
Criteria 2		7	2	1

Criteria 3	3	3
Criteria 4		4

Figure 1: Example of Pair-Wise Comparison Matrix

Included in Sub-Appendix G-A, on pages G-A-4 through G-A-12, are the sheets that contain the input data for the pair-wise comparison. The first sheet (page G-A-4) contains a comparison of all of the objective's factors. The remaining sheets contain comparisons of criteria relative to each factor. The numbers in the matrix indicate that the row element is n times more important than the column element. Unless the value is in parenthesis, in which case the column element is n times more important than the roll element.

The next step in the hierarchical analysis process is to determine the alternatives and rate them. Determining the alternatives was fairly straightforward since data was only submitted for seven concepts. These were:

- Concept 1: Combined Cycle Propulsion, Mach 12 to Rocket, Vertical Take-off / Vertical Landing (VTVL)
- Concept 2: Combined Cycle Propulsion, “Argus”, Mach 6 to Rocket, Horizontal Take-off / Horizontal Landing (HTHL), With Launch Assist
- Concept 3: Combined Cycle Propulsion, “Waverider”, Horizontal Take-off / Horizontal Landing (HTHL), With Launch Assist
- Concept 4: Rocket, BCS Updated Baseline, Vertical Take-off / Horizontal Landing
- Concept 5: Rocket, BCS Updated Baseline, with Low Maintenance, Light Weight, High Performance Engine, Vertical Take-off / Horizontal Landing
- Concept 7: Rocket, Two Stage To Orbit, Hydrocarbon Fuels, Vertical Take-off / Horizontal Landing
- Concept 8: Combined Cycle Propulsion, Mach 15 To Rocket, Horizontal Take-off / Horizontal Landing

The project breakdown chart lists the concepts separate from the factors and criteria. In fact, the ECPro software package considers the alternatives as a sub-factor for each of the lowest level sub-criteria in the model. In other words, a pair-wise comparison is performed relative to each of the lowest level criteria. The program then takes the results of these comparisons and works back to the objective level factoring in the higher level preference rating as it goes.

The scoring for each alternative was based on the results of the survey, where each concept was self-evaluated by its developer. Unfortunately, this does not work well with a pair-wise comparison. If a true pair-wise comparison was used each developer would have rated their project relative to all of the other concepts. Besides the problem of proprietary data, pride in one’s design would likely result in very inconsistent results from developer to developer.

To eliminate this problem we used the ratio of scores of a pair of concepts to determine the scoring. For example, if Concept A had a score of 5 and Concept B had a score of 2, then Concept A was scored as two and one-half times better than Concept B. The difference between this and the pair-wise comparison is that under pair-wise comparison each comparison is independent. What impact this has on the results is unknown. Because the ratio of scores method of scoring is much less time consuming, additional study is needed in this area. (Further discussion of this will be included in the conclusions and recommendations section.)

The results of the project analysis are presented are presented in Table 1 and graphically on page G-A-13. Note that the results of the ECPro model are relative scores, and any attempt to infer information from the absolute scores is not advisable. What are important are the relative values of the scores. Note that the top four concepts have combined cycle propulsion systems. After the CCP concepts are the more traditional all rocket single stage to orbit vehicles. Finally, the last, or least preferable is the traditional two stage system. These results appear to strongly support the development of a combined cycle propulsion system.

The results also appear to favor new technology over traditional launch systems. Concepts 4, 5, and 7, which are one and two stage all-rocket systems have scores significantly lower than the combined cycle propulsion system. This trend also appears in the combined cycle concepts, where the more conventional Argus system scored considerably less than other CCP concepts.

Table 1: Survey Based Model Results

Concept	Score
3. CCP, “Waverider”, HTHL, with Launch Assist	.163
8. CCP, Mach 15 to Rocket, NDV, HTHL	.158
1. CCP, Mach 12 to Rocket, VTVL	.152
2. CCP, “Argus” – Mach 6 to Rocket HTHL, with Launch Assist	.144
4. Rocket, BCS Updated Baseline, VTHL w/ ACRE	.130
5. Rocket, BSC w/ACRE	.130
7. Two Stage To Orbit, Hydrocarbons, VTHL	.122

The model results also show mixed results for launch assist. While the “Waverider” concept using launch assistance received high scores, the “Argus” concept using launch assist did not. This can be interpreted as saying that launch assistance has value over traditional methods of launching, but not enough to make up for the difference between higher technology and traditional launch vehicles. In other words, the “Argus” concept was better than the baseline all-rocket concept, but not enough to bring it up to the level of the high technology CCP concepts.

Another way to look at the results is to determine how sensitive they are to changes in the factor preferences. Sub-Appendix G-A, pages G-A-14 through 22, illustrate the differences cause by changes in preferences. Page G-A-14 shows the baseline results. The color bands on the scoring bar of each concept represents the contribution of each factor to that concept’s score.

The sensitivity of the results was determined by varying the preference of each factor one at a time. Pages G-A-15 through 22 represent the results of the analysis if each of the objective’s factors, in turn, is given a preference weight of 50%. Note that regardless of which factor is given more weight, concepts 3, 8, and 1 remain at or near the top of the scoring. This would indicate the solution is not real sensitive to changes in the factor weights. The following table summarizes the relative effect of increases in preference weight for each factor.

Table 2: Impact of Sensitivities on Weights

Factor Increased:	Concepts Losing	Concepts Constant	Concepts Increasing
Propulsion	3,4,5	-	1,2,7,8
Structures	1,8	-	2,3,4,5,7
Safety / Reliability	1,3,7	4,5	2,8

Ground Processing	2,3,4,5	8	1,7
Infrastructure	1,2,5	4	3,7,8
Manufacturing	4,8,7	-	1,2,3,5
Launch Operations	1,2,3,7	-	4,5,8
Maintenance	2,8	5	1,3,4,7

Because this was the first time we had used hierarchical analysis techniques in the analysis of a space transportation system, we needed to validate the model. The most direct way to do this was to compare results with other methods. By comparing the rank ordering of alternative systems, we found that the results were similar, but not exactly. There are several reasons why there could be a variation in the results, including differences in the preference vector, differences in ranking of alternatives, or a problem with the model.

To determine the cause we decided to use the alternative scoring from the KSC Architectural Assessment Form (AAF) model as a comparison. The KSC data consisted of their scoring of alternatives against the first 31 questions on the survey. This was compared with the manufacturer self-evaluations for the first 31 questions. Both sets of data were run though the survey model, which had been modified for using only 31 questions. The results are show in Table 3:

Table 3: Comparison of Results

Concepts	Self-Evaluation (37 Questions)	Self-Evaluation (31 Questions)	KSC-Evaluation Survey Model	KSC-Evaluation AAF Model
CCP, Mach 12 To Rocket, VTVL	3	4	2	5
CCP, "Argus"	4	3	1	4
CCP, "Waverider"	1	1	3	6
Rocket, Baseline	5	6	4	1
Rocket, w/ACRE	6	7	5	3
TSTO, Rocket	7	5	6	2
CCP, NDV (LACE)	2	2	7	7

The results of the Self-Evaluation (31 Questions) and KSC-Evaluation (Survey Model) can be found on pages G-A-23 and G-A-24 respectively. The KSC-Evaluation (AAF Model) can be found in Appendix E of is report.

From these results, it appears that there are several differences between the hierarchical analysis model and the KSC AAF model. The most likely cause of the differences is the weighting of factor and criteria and the scoring of alternatives. The impact of the number of questions used is minimal as illustrated in the comparison of scores using the self-evaluation scoring. The differences in the two KSC-evaluated models can probably be traced to differences in weighting of preferences since both used the same data, but with different models and preferences. On the other hand, the self-evaluation and KSC-Evaluation (Survey Model) used the same model and preferences, but different scoring of alternatives.

What this says is that any conclusions from this survey are highly dependent on the rater's preferences and their view of the alternatives. At this stage with few objective measures the variations in results is expected. It should be noted that the preferences between the models might differ because the preferences came from different points of view. The KSC model results are based on the viewpoint of hands-on operations, while the survey model preferences were based on a designer's point of view. In addition, the developers scored the questions of the survey model, while experience launch operations personnel scored the KSC models. The developers appear to be much more optimistic.

Mankins' Model

Appendix K contains the information from the Mankins' Model. For this model, the same objective was declared. That is to select the most promising HRST candidates for further development. Mr. Mankins then broke this down into eleven factors: Passive propulsion systems, active propulsion systems, active vehicle systems, passive vehicle systems, payload, crew accommodations, operations and maintenance, launch processing, launch support, propellant operations, and landing.

The number of factors created a problem since the Expert Choice ECPro software package allows only 9 breakouts from one level to the next. Adding a super factor level between the objective and the given factors solved the problem. This level has a Vehicle group consisting of the first six factors and a Ground Systems group consisting of the remaining five factors. Since the super factor level was an artificial construction to allow the model to run under ECPro, it should not have any influence on the final result. To assure this, the initial super level preferences were set so that each factor would have an equal impact on the objective.

Sub-Appendix G-B contains the data sheets received from Mr. Mankins showing his breakdown factors and criteria. Like Sub-Appendix G-A, Sub-Appendix G-B also contains the model breakdown structure and the list of model definitions. (Pages G-A-1 through 4)

As before, the next step in the hierarchical analysis is to conduct a pair-wise comparison to determine the preference vectors. Because the data provided also contained preference ratings for factors and criteria, we decided to use the data. As in the case of the alternative comparisons for the Survey Based Model, a pair-wise comparison was not practical. Again we used the ratio of scores method to provide "pair-wise comparisons".

The results of the comparisons for the Mankins Model are in Sub-Appendix G-B, pages G-B-5 through 15. These sheets contain comparisons of criteria relative to each factor. The numbers in the matrix means that the row element is n times more important than the column element. Unless the value is in parenthesis, in which case the column element is n times more important than the roll element.

Because of the large number of factors, criteria, and sub-criteria, it was not possible to score the alternatives for this model within the time given. This action was deleted from this analysis.

<u>Summary of Results:</u>

Based on the results from the survey-based model, several observations can be made.

- The results of the model favor a combined cycle propulsion system. All of the CCP powered concepts scored at the top of the results. With the exception of the "Argus" CCP, all of the CCP powered concepts scored significantly better than the rocket-based concepts, both one and two stage.

- The results showed a preference for new designs. The top three scoring alternatives all had combined cycled propulsion systems, while the bottom three had conventional rocket propulsion. If there was a bias toward to technology, it should not be surprising, since the driving point of this study was to identify promising new technologies.

- The impact of launch assistance was uncertain. Two launch assist concepts were submitted, both powered by a CCP system. One scored very high, and the other very low. The low value belonged to the "Argus" concept, which was the most conventional of the CCP concepts. In fact, its actual score was more in line with the all rocket systems than with the other CCP concepts. The difference in scores could be an indication that launch assist is not a major discriminator in the scoring decision.

- Finally, the results of the analysis did not appear to be sensitive to changes in preferences. The three highest scoring concepts in the study results were among the strongest contenders regardless of the preference matrix.

<u>Conclusions and Recommendations:</u>

Most of the conclusions and recommendations are based on the hierarchical analysis process rather than the results of the analysis. This project was one of our first uses of the analytical hierarchy process and the Expert Choice "ECPro" software. As a result, this has been a learning process. With respect to the method and approach of the analytical process we have the following comments:

The survey-based model was built upon a self-assessment of each concept by its developers. Self-assessment has several drawbacks in this process. First, most of the multiple-choice questions had an obvious "right" answer. In other words, since low cost was a major push of this project, selecting the choice that was the least expensive was obviously the right answer.

Additionally there may be some problems with developers being objective in grading their own concept. With the use of only subjective questions, the process could turn into a game of "Liar's Poker". A solution to this would be for each developer to do a pair-wise comparison of all other concepts. Unfortunately, this is impossible due to proprietary data considerations.

In several areas, preferences in the survey-based model and comparison of concepts in the Mankins' model, pair-wise comparisons were necessary. Because project manpower was performing other analyzes; I completed the pair-wise comparison based on my "expert" opinion of launch vehicle operations. While this type of analysis provides quick results, better quality results can be achieved through multiple independent analysis and averaging, or by group discussions. The latter methods should be the approach of choice, although experience shows they are very time consuming.

In two areas, scoring of alternatives for the survey-based model and preferences for the Mankins' model, a score ratio approach was used in place of pair-wise comparisons. In both cases pair-wise comparison was abandoned because of the amount of time it would take to complete a pair-wise comparison and that the data required for ratios was already available. In the modified baseline approach, the pair-wise comparison values were calculated from the ratios of ranked data. The result is that the data is completely consistent, where with pair-wise comparisons which independently rank each pair normally would have a degree of inconsistency. The goal of any pair-wise comparison is to achieve complete consistency, yet the modified baseline method appears to do it in a contrived manner. Because the score ratio approach has the potential to save considerable time and effort, further study is needed to determine its impact on model results.

- Both models of this study were based entirely on subjective questions. The use of only subjective questions gives the study the appearance of being on shaky ground, since everything is based on opinion. While ECPro has the capability to work with all subjective data, a greater stability can be arrived at by including objective data where possible. This also makes the pair-wise comparison of data easier since there is less a question of what the data actually means and how it compares to other data.

- Comparison of results between this method of analysis and other methods showed that any method at this stage of development is highly dependent on the rater's preferences. To determine the best results would be to determine the most acceptable set of assumptions and preferences. Hopefully as the design solidifies the factor and criteria become more objective, and the results will converge.

This project was an excellent first use of the analytical hierarchy method. Later applications will benefit from what was been learned here. As for the results of this study, they can only be considered relative to the input data, and their importance by the value placed on them by the manager.

Highly Reusable Space Transportation
Integration Task Force

Operations Assessment Team
Request for Information

Concept Title: **_____**

June 29, 1997

Concept Developer Information

Concept Title	_____
Organization	_____
Principle Investigator	_____
Point of Contact	_____
Telephone / Fax	_____
E-Mail Address	_____

Index

Introduction

This Request for Information is part of the Highly Reusable Space Transportation (HRST) Integration Task Force. The HRST Integration Task Force is tasked to "synthesize results in several topic areas" and to "support the development of conclusions from the HRST study". The Operations Assessment Team, one of four parts of the task force (the others are Systems Concepts Definition, Technology Assessment, Cost Assessment Teams), is focused on defining and conducting operations assessments for HRST concepts.

This Request for Information will be complimented by other sets of information that are expected to be available including the (1) Propulsion System Information Worksheet (which was disseminated at the March 1997 Propulsion Workshop), (2) Vehicle System / Cost Information Worksheets (TBD), (3) Cost Input (Excel Workbook) and (4) Operations Simulation and Analysis Modeling System (OSAMS) Minimum Data Input sheet (Excel Workbook). The Cost Input and OSAMS Data Input documents are attached to this Request.

This Request is in large part based directly on the Space Propulsion Synergy Team's *A Guide for the Design of Highly Reusable Space Transportation*, November 18, 1996, Rev. Basic. We strongly recommend that you obtain the *Guide*, which can be downloaded from the Virtual Research Center (see Item 4 of General Instructions (below.))

The operation of a space transportation system will directly determine recurring costs. The HRST project goal of identifying concepts and associated technologies that will enable recurring payload costs in the range of $100 per pound requires an understanding of the operation of the system. For space transportation systems {being defined} in early conceptual phases this assessment of "operability" requires obtaining and integrating information that allows defining both a possible and likely scenario of operations. A comparison among concepts and technologies with regard to the ability of each to achieve affordable space transportation is then possible.

Questions regarding this Request for Information should be directed to the Operations Assessment Team leads, Mike Nix at Marshall Space Flight Center, (205) 544-7877 or Carey McCleskey at Kennedy Space Center, (407) 861-3775.

General Instructions

This Request is composed of two parts, Part 1, Assessment Form - System Design and Programmatics, and Part 2, Specific Concept Data.

Instructions:

1. Part 1, Assessment Form - System Design and Programmatics is a multiple-choice format. The possible answers to a question are ordered with respect to each other in decreasing degree of “operability”.

2. Part 2, Specific Concept Data requests specific information on the concept, to be filled in as indicated.

3. Recognizing that not all information may be available at this phase, please indicate where concept definition does not yet allow a clear answer.

4. Documents that are referenced “VRC” can be found at the following internet address via the Virtual Research Center (VRC) Operability Wing: http://moonbase.msfc.nasa.gov/ (For information on obtaining password access into the VRC, please contact Mr. Nix (above) or Mr. Daniel O’Neil (205-544-6618.)

5. An electronic version of this document is located at the Internet address above.

6. Notes by the concept originator explaining individual answers in these sheets are recommended (but not required) as they will better assist the Operations Assessment Team and reduce later clarification requests. Published papers, presentations or other documentation on the concept or major new technologies utilized in the concept would also assist the team in understanding the concept. Please indicate at appropriate specific questions that such supporting or supplemental documentation is attached.

Highly Reusable Space Transportation Architectural Concepts

- An Assessment Form for Characterizing the Reusability and Affordability of Space Transportation System Concepts

- Each HRST Architectural Concept provides a generic Summary Sheet for communication and assessment

System Design
Part 1.1

Concept Title ____

- **Identify the overall *propulsion concept* for assessment:**

_____	• All Rocket
_____	• Combination Cycle
_____	• Rocket-Based Combined Cycle (RBCC)
_____	• Launch Assist/All Rocket
_____	• Launch Assist/RBCC
_____	• Launch Assist/Combination Cycle
_____	• Microwave Beaming
_____	• Very Advanced (Specify) _____

Notes
(Part 1.1 Only)

Each numbered assessment category in Part 1.1 contains a cross-reference to particular design feature(s) (DF) that may be found in the Space Propulsion Synergy Team's *A Guide for the Design of Highly Reusable Space Transportation*, November 18, 1996, Rev. Basic. (e.g., designations such as *DF #6*). This guide contains more specific information regarding the assessment items in this form.

Designations of "STS" or "ATS" on the assessment form indicate the current state-of-the-art in each numbered assessment category.

> *STS* — refers to the Space Shuttle (Space Transportation System) baseline
>
> *ATS* — refers to the Access-to-Space study (Option 3) all-rocket single stage to orbit (SSTO) vehicle (the HRST study project's reference vehicle)

NOTE: Section 1.1 (Questions 1-18) is identical to Section 1.1 in the "Architectural Assessment Form" included in Appendix E (prior.)

Programmatics
Part 1.2

Notes
(Part 1.2 Only)

The numbered assessment questions in Part 1.2 have been developed by the HRST Operations Assessment Team as a supplement to those in the original *HRST Architectural Assessment Form* (Part 1.1.) They are not cross-referenced to particular *Guide* DF's. However, responses to these questions will enable the Assessment Team to gain additional insight to the operational characteristics of the concept.

19. Infrastructure - Ground Support Facilities - Transportation of vehicle to launch site (initial, depot, or abort site):

_____	Manufacturing and depot level maintenance are accomplished at the launch site.
_____	Vehicle has self ferry capability from manufacturing and to depot location.
_____	Vehicle can be moved intact using air transportation between launch site and manufacturing and depot locations.
_____	Vehicle can be moved intact using surface transportation (barge, road, or rail) between launch site and manufacturing and depot locations.
_____	Vehicle must be disassembled for transportation requiring reassembly at launch and depot locations.

20. Infrastructure - Ground Support Facilities - Transportation around launch site:

_____	Vehicle can be towed around launch site on its landing gear using standard aircraft towing equipment. Launched from horizontal position either ground or air.
_____	Vehicle can be towed around launch site on its landing gear using standard aircraft towing equipment, then raised to vertical position for launch.
_____	Vehicle must be placed on simple trailer with landing gear retracted, then raised to vertical position for launch.
_____	Vehicle must be placed on trailer with support GSE and tilt mechanism for raising vehicle to vertical.
_____	Vehicle is place on a mobile launch platform in the vertical position and transported around launch site on mobile launch platform.

21. Infrastructure - Ground Support Facilities - Continuing maintenance of group support facilities:

______	Small and simple facilities, with minimal GSE, requiring little or no continuing maintenance.
______	Small and simple facilities, with minimal GSE, requiring continuing maintenance after a specified number of flights.
______	Facilities and GSE in line with current expendable launch sites, requiring continuing maintenance after a specified number of flights.
______	Facilities and GSE in line with current expendable launch sites, requiring continuing maintenance after each flight.
______	Facilities and GSE in line with current Shuttle, requiring continuous maintenance.

22. Infrastructure - Manufacturing Operations - Facility requirements:

______	Launch vehicle can be manufactured with current facilities and machinery.
______	Launch vehicle can be manufactured with current facilities and requires common industry machines.
______	Launch vehicle can be manufactured with current facilities, but requires entirely new manufacturing process with new and specialized machine tools and equipment.
______	Manufacturing facility must be modified to accept new process, and specialized tools and equipment.
______	Entirely new manufacturing facility is required with new manufacturing processes and specialized tools and equipment.

23. Infrastructure - Manufacturing Operations - Transportation of components to manufacturing site:

______	Components are small and not hazardous and can be transported using all commercial transportation without special permits. Manufacturing facility has direct access to all transportation modes.
______	Components are outsized and must be transported using surface transportation using special permits. Manufacturing facility has ready access to surface transportation.
______	Components are outsized or commonly used industrial hazardous materials requiring special permits. Manufacturing facility has ready access to surface transportation.
______	Components are outsized and must be transported using surface transportation requiring special permits. Manufacturing facility is away from main surface transportation routes.
______	Components are outsized and very hazardous (e.g. solid rocket motors), requiring special permits and routing. Manufacturing facility is away from main surface transportation routes.

24. Infrastructure - Manufacturing Facilities - Environmental Concerns

_____	Manufacturing facility is totally environmentally friendly, does not require hazardous substances for production, nor are any hazardous substances produced during production of the launch system.
_____	Manufacturing facility uses standard industrial materials and processes, which are contained and recycled.
_____	Manufacturing facility uses standard industrial materials and processes, which are contained but not recycled. Waste material stored in standard environmental dump sites.
_____	Manufacturing facility uses extremely hazardous materials and processes, which are contained but not recycled. Waste material must have special facilities for storage of waste.
_____	Manufacturing processes and materials are extremely hazardous and must be house in special facilities located away from populated area.

25. Infrastructure - Manufacturing Facilities - Safety Concerns:

_____	Manufacturing processes and materials do not pose a safety problem with surrounding areas.
_____	Manufacturing processes and materials do not pose a safety problem greater than that of any general manufacturing facilities.
_____	Manufacturing processes and materials pose a significant safety problem that can be contained using special operating procedures.
_____	Manufacturing processes and materials pose a significant safety problem to the point that special facilities and procedures are required.
_____	Manufacturing processes and materials are extremely hazardous and must be house in special facilities located away from populated areas.

26. Infrastructure - Manufacturing Operations - Continuing Maintenance:

_____	Small and simple facilities, with minimal standard industrial machinery, requiring little or no continuing maintenance.
_____	Small and simple facilities, with standard industrial machinery, requiring continuing maintenance after a specified number of production cycles.
_____	Standard manufacturing facilities with standard industrial machinery, requiring continuing maintenance after a specified number of production cycles.
_____	Standard manufacturing facilities with specialize industrial machinery and process requiring specialize recurring maintenance requirements.
_____	Large facility with specialized manufacturing processes and tools, requiring continuous maintenance

27. Manufacturing Operations - Unique Processes Or Hardware

_____	Manufacturing processes consist of standard machine and metal fabrication techniques using standard materials and tools.
_____	Manufacturing processes require close tolerance work, but consist of standard machine and metal fabrication techniques, materials, appropriate tools.
_____	Manufacturing processes and materials required extensive machining at close tolerances requiring some special machines and tooling.
_____	Manufacturing processes and materials require highly specialized, state -of-the art machining and fabrication techniques.
_____	Manufacturing processes and materials requiring a significant research and develop process before manufacturing can be started.

28. Manufacturing Operations - Manufacturing Complexity

_____	Fabrication and assembly of launch system involves basic machining and assembly practices that can be complete by most machine shops.
_____	Fabrication and assembly of launch system involves machining and assembly practices on line with an automobile plant.
_____	Fabrication and assembly of launch system involves machining and assembly practices on line with an aircraft plant.
_____	Fabrication and assembly of launch system involves specialized equipment and techniques, and long learning curves, but vehicles are identical.
_____	Fabrication and assembly of launch system involves specialized equipment and techniques, and long learning curves, but each vehicle is unique.

29. Manufacturing Operations - Percent Assembly At Site

_____	Manufacturing and launch facilities are on the same site.
_____	Manufacturing is in local vicinity of launch site; minimal in-processing is required at the launch site.
_____	Manufacturing and launch facilities are located at widely separated locations, but the vehicle can be shipped in tact and requiring only in-processing at the launch site.
_____	Manufacturing and launch facilities are located at widely separated locations, and the vehicle must be shipped as major components requiring assembly at the launch site.
_____	Manufacturing is at separate location and vehicle is assembled at the launch site.

30. Ground Processing Operations - Operational Complexity

_____	Aircraft-style turnaround with checkout, maximum use of line replaceable items, fuel, and go.
_____	Aircraft-style turnaround with the exception of engines. Engines will have an integrated health monitoring system.
_____	Fairly complex vehicle requiring extensive checkout before next flight. Turnaround assisted by Vehicle Health Monitoring (VHM) throughout the vehicle.
_____	Complex system requiring extensive repair/replace operations, with minimal VHM. Each vehicle turnaround is tailored to that specific vehicle.
_____	Shuttle type turnaround operations with large infrastructure, complex system checkout requirements, and depot level maintenance before each flight.

31. Launch Operations - Vehicle Design - On-Pad Maintenance

_____	No vehicle maintenance required on-pad, failures at pad result in roll-back, simplified interfaces, no payload access at pad, time on pad less two days.
_____	Minor vehicle maintenance allowed at pad, simplified interfaces, payload installation occurs before moving to the pad, but late payload access is allowed. Pad stay time of less than 5 days.
_____	Minor vehicle maintenance allowed at pad, simplified interfaces, payload installation and access allowed at pad. Pad stay time is less than a week.
_____	Extensive maintenance is allowed at pad (e.g. engine removal). Simplified interfaces, payload installation and access allowed at pad. Pad stay time of less than 2 weeks.
_____	Shuttle type on-pad procedures. Complex interfaces with considerable checkout required. Payload loading and access allowed at pad. Extensive on-pad maintenance is allowed. Pad stay time measured in weeks.

32. Launch Operations - Vehicle Design - GSE Requirements

_____	Common “aircraft style” GSE including jacks, lift rigs, “start carts”, and other equipment for test, checkout, and servicing vehicle. GSE for individual components is not required.
_____	GSE specific to launch system but simple in nature including jacks, lift rigs, test and checkout equipment for vehicle systems. GSE for individual components is not required.
_____	GSE specific to launch system, but simple in nature including jacks, lift rigs, test and checkout equipment for vehicle system and its components.
_____	Extensive GSE is required for servicing, test, and checkout. GSE is specific to launch system and its components. GSE requires only basic continuing maintenance on the level of other machine tools.
_____	Shuttle style GSE, extensive GSE that is unique to individual components of the launch system, required extensive continuing maintenance, and large logistical support system of its own.

33. Launch Operations - Scrub Turnaround

_____	System requires no scrub turnaround time and is ready for launch in a moment’s notice.
_____	System can be turned around for relaunch within 12 hours, with no limit on the number of attempts.
_____	System can be turned around for relaunch within 24 hours, with no limit on the number of attempts.
_____	System can be turned around for relaunch within 24 hours, but the capability is limited to two or three days.
_____	System has Long and complex launch process requiring several days to turnaround for next launch opportunity.

34. Launch Operations - Environmental Constraints To Launch

_____	Very robust vehicle that can be launched and recovered with weather restrictions similar to those on commercial aircraft.
_____	Robust vehicle that can be launched and recovered even in rain and winds of up to thirty knots in any direction.
_____	Robust vehicle that can be launched and recovered even in winds of up to thirty knots. Rain restricts launch but cloud cover does not.
_____	Robust vehicle that can be launched and recovered even in winds of up to twenty knots. Rain restricts launch but cloud cover does not.
_____	Launch constraints similar to current Shuttle requirements.

35. Launch Operations - Safety

_____	Vehicle can be operated from any location such as a commercial airport.
_____	Vehicle can be operated from any commercial or government space port.
_____	Vehicle restricted to standard launch sites and ranges. (e.g. KSC/CCAFS, Vandenburg).
_____	Vehicle must be launched from a remote area with population areas at least 15 miles away.
_____	Vehicle must be launched from a remote area, with populated areas at least 50 miles away.

36. Mission Operations - Support Crew Size

_____	Launch vehicle mission length (after MECO) is so short that launch crew can accomplish it.
_____	Launch vehicle mission length up to 12 hours, but vehicle is highly autonomous and mission command and control can be handled by less than 10 people
_____	Mission operations are completed within 24 hours, but vehicle is highly autonomous and mission command and control can be handled by less than 10 people.
_____	Launch vehicle mission length up to several days. Vehicle is not autonomous and requires extensive command and control.
_____	Missions can extend up to a week with an extensive (>25) person crew, providing 24 hours command and control of the vehicle.

37. Missions Operations - Monitoring Complexity

_____	Vehicle is highly autonomous with ground providing a back-up systems monitoring capability.
_____	Vehicle is autonomous but requires ground support for anomaly correction actions.
_____	Vehicle requires monitoring and top level command and control from ground, but can autonomously carry out complex tasks when ordered from ground.
_____	Vehicle systems are monitored by on-board systems providing anomaly data to ground. Ground performs all command and control functions.
_____	Basically a “dumb” vehicle requiring extensive monitoring of systems and command and control.

Appendix H - Parametric Operations & Maintenance Hours Estimating Tool (PrOpHET)

INTRODUCTION

The idea of estimating the O&M hours required to process (operate, maintain) a space transportation vehicle from dry weight of vehicle subsystems was conceived during the HRST integration activity by John Mankins, NASA HQ.

Labor costs associated with normal operations and maintenance (O&M) can constitute one of the largest components of recurring operations costs for any HRST ETO concept. However, an accurate grass-roots estimate of O&M labor requirements cannot be constructed without detailed information regarding the specifics of vehicle and ground systems. This level of detail cannot be developed in an initial concept definition effort, e.g., HRST. Nevertheless, it is clear that various HRST concepts will involve very different O&M requirements

Using a "flat" estimate (e.g., "200 FTE" or "400 FTE") for all concepts would mask key differences between the concepts being assessed. The challenge then is establishing an approach to HRST O&M-related labor cost estimation in the absence of complete information. Three groundrules must be observed: 1) Develop estimates that are based on true discriminators in O&M requirements; 2) Assure <u>relative</u> consistency between estimates for the different concepts and 3) Develop an approach that encompasses both fixed and variable O&M costs.

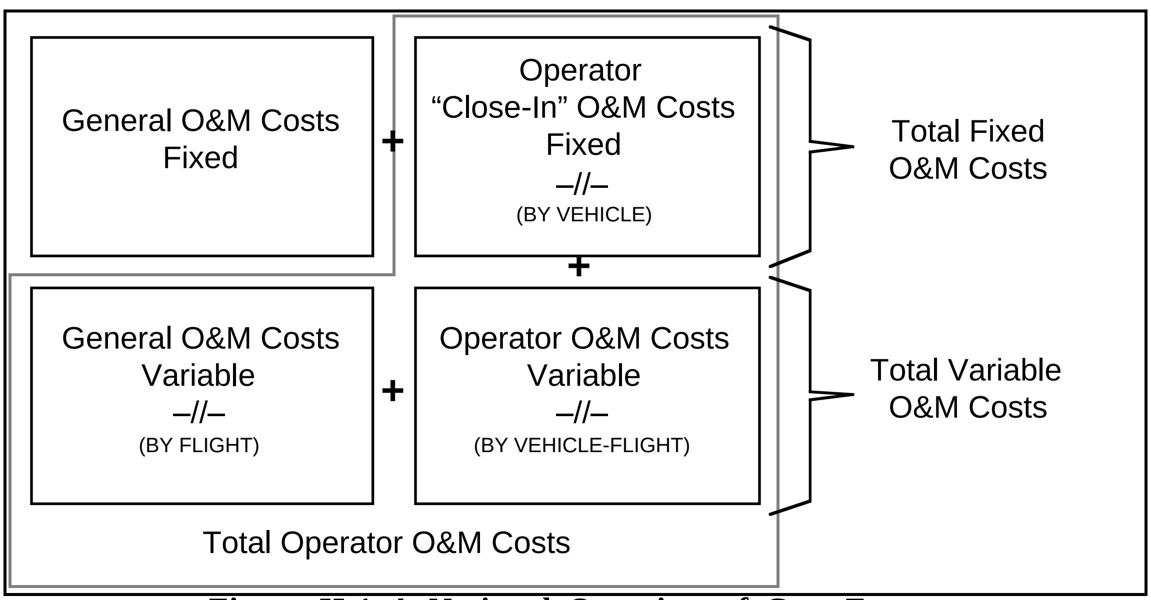

Figure H-1 A Notional Overview of Cost Factors

APPROACH

Start with a single O&M Metric: Labor Hours per Flight per Pound of Vehicle Hardware. Use the Space Shuttle O&M Labor data to anchor the Baseline Comparative System (BCS) as a common point of departure. Modify the Access-to-Space, Option 3, All-Rocket SSTO, vertical takeoff/horizontal landing (VTHL) by using the Shuttle data to project equivalent O&M requirements.

The BCS requires approximately 4400 FTE to support 40 flights per year for an SSTO with a Dry Mass of about 235,000 lb. This is equivalent to 10 flights/year per vehicle for 4 vehicles in the operational Fleet, which is equivalent to about <u>4 hrs per flight per pound of vehicle dry mass.</u>

Assume that about 30% of the hourly charge is a variable cost dependent on the vehicle systems for which O&M is being provided, and that about 70% is for fixed costs where the ratio of non-touch labor to touch labor is approximately 3:1; this yields:

> Variable O&M Labor equals <u>1.2 hrs per flight per pound of vehicle Dry Mass</u> or about 1320 FTE's and
>
> Fixed O&M Labor equals <u>about 3080 FTE's</u> or about 2.8 hrs per flight per pound of vehicle Dry Mass

Next, assume that about 20% of the total O&M charge is associated with "Close-In" operations provided by the Vehicle operator, and that about 80% of the total O&M charge is associated with "General" support to the vehicle operator; starting with 4400, this yields:

> "Close-In" O&M Labor equals 880<u> FTE's;</u> which is equivalent to [Fixed: about 616] + [Variable: about 264] FTE's
>
> "General Support" O&M Labor equals<u> 3520 FTE's</u>; equivalent to [Fixed: about 2464] + [Variable: about 1056] FTE's

NOTE: <u>General Fixed O&M Costs will be treated separately later</u>

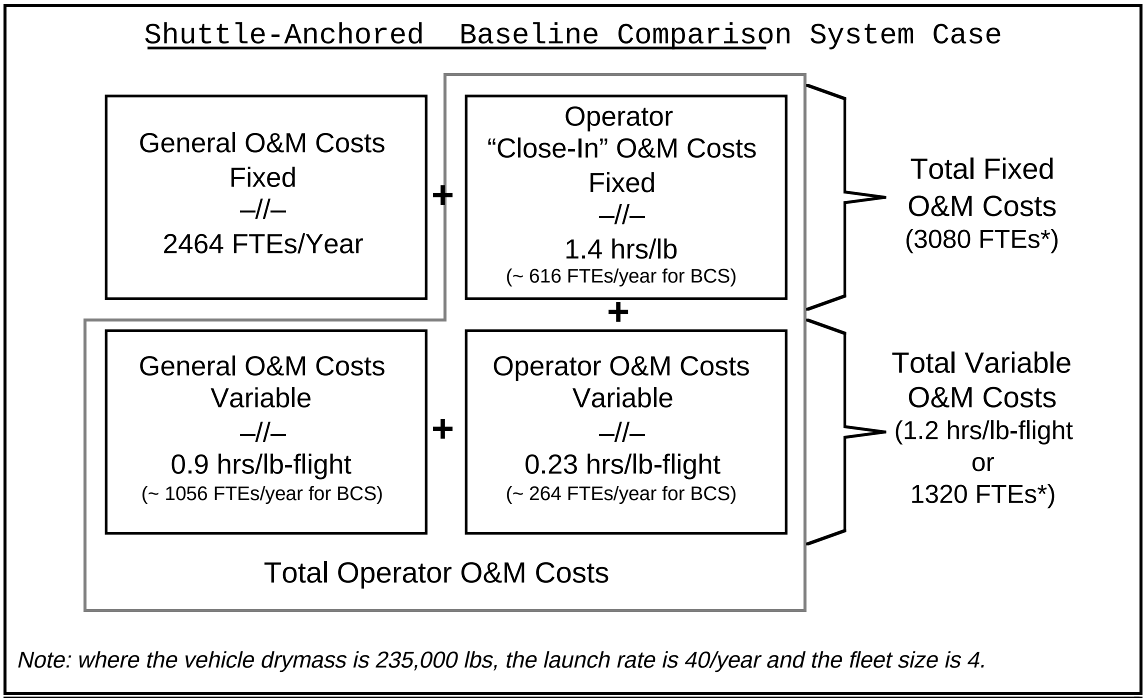

Figure H-2 Proposed O&M Cost Factors Matrix-Shuttle Anchored

Therefore, as a revised starting point for the BCS we'll use

Variable O&M Labor equals 1.2 hrs per flight per pound of vehicle dry mass (about 1320 FTE's)

About 330 FTE's per vehicle for a fleet of 4

Fixed O&M Labor equals About 3080 FTE's (about 2.8 hrs per flight per pound of vehicle dry mass)

Or...

"Close-In" O&M Labor: equals about 880 FTE's; which is equivalent to [Fixed ~ 616] + [Variable ~ 264] FTE's

Where Close-In Variable equal about 264 FTE's or equivalent to 0.23 hrs/dry mass lb.-Flight

"General Support O&M Labor: ~ 3520 FTE's; equivalent to [Fixed: about 2464] + [Variable: about 1056] FTE's

Where General Support Variable equal about 1056 FTE's or equivalent to 0.94 hrs/dry mass lb.-Flight

During the next 10 years, there will be advances in materials, sensors, integrated vehicle health management (IVHM), robotics, etc., that will benefit O&M for all HRST concepts (Note, However, that any "Leapfrog" improvements must be enabled by vehicle design.)

As a goal, we will project the resulting improvement to be about 10:1; then the adjusted baseline for O&M Labor becomes:

Variable: about 0.11 hrs per flight per pound of vehicle Dry Mass
____= [Vehicle Specific: about 0.023 hrs/lb.-flight] + [General Support: about 0.09 hrs/lb.-flight]
Fixed: about 308 FTE's/year

____= [Vehicle Operator Specific: about 62 FTE's/year] + [General Support: about 246 FTE's/year]

Finally, Operator Specific Fixed will be "converted" to a pseudo-variable by putting in on a per pound of vehicle basis so that 62 FTE's/Year becomes about 0.14 hrs per dry mass pound.

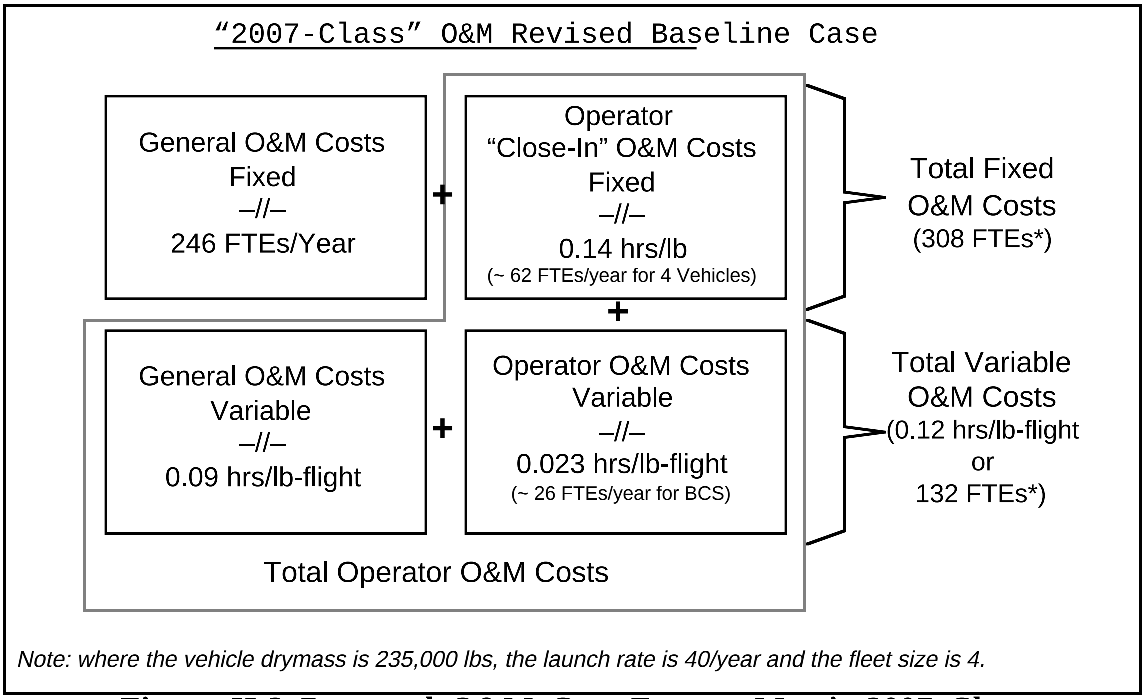

Figure H-3 Proposed O&M Cost Factors Matrix-2007 Class

Ultimately, we need to deal with the three types of O&M costs distinctly:

1) Common, Fixed O&M we will treat by a simple algorithm (2% of the value of the facilities)

2) No additional use will be made of the FTE number on the previous page for Fixed O&M

Next, we need to treat separate the "Fixed" component of the Close-In, Operator-Specific O&M Costs. This will be treated after the next section.

Finally, we can treat the 2 components of the Variable Cost (Close-In and Common) as being paid for by the Vehicle Operator - and therefore as a single revised O&M parameter

In addition, there is a real variation in the labor associated with O&M for different types of vehicle hardware: a great deal for active propulsion systems; Very little for the airframe (if designed properly and built out of appropriate materials), etc. etc.
Therefore, further adjustments are needed to take into account variations in the O&M requirements of the various major pieces of the vehicle. A rigorous study is needed based on known surrogates (e.g., Shuttle.)

For this exercise, a high-level disaggregation of vehicle systems is needed.

<u>Therefore, for HRST Vehicle Variable O&M...</u>

Beginning with this <u>adjusted</u> O&M parametric to account for all Variable O&M requirements: 0.11 <u>hrs per flight per pound of vehicle Dry Mass</u> where each labor hour will be costed at $120,000 per year (about $60/hour.)

Then, adjustments to this parametric can be made for each of the major types of hardware in a vehicle system concept, in descending order of importance to O&M:

- Vehicle Systems – Active
  - e.g., subsystems such as GN&C and EMA's, active thermal protection systems
- Vehicle Systems – Passive, with two elements
  - First element: Thermal Protection Systems
  - Second element: everything else, such as primarily structures, general insulation, etc.
- Propulsion Systems – Active, with two elements
  - First element: primary propulsion system(s)
  - Second element: OMS, RCS, miscellaneous pumps, etc.
- Propulsion Systems – Passive
  - e.g. tanks, insulation on tanks, plumbing, passive inlets

Then the Question Is: Which of these are the most important to O&M costs?

HRST Operations Cost Analysis

Indicators of Required Vehicle-Driven O&M Labo

	O&M Indicator(s)	Rationale
Propulsion Systems (Active) Primary Propulsion	Number/Diversity of Engines Number of Propellants/Hazard Potential Expected T/W Margins ("derating") that could be achieved in Operations Level of IVHM Utilization	Number/Diversity of Propulsion Systems will drive labor, LRUs, etc. Number of propellants increases number of labor hours Heavier stresses on systems will require increased levels of maintenance
Vehicle Systems (Passive) Thermal Protection Systems	Passive Thermal Protection System Robustness, Type(s) and Total Area Level of IVHM Utilization	TPS maintenance will drive O&M labor related to this category Large/complex structural forms will have higher stress, more nook/crannies to inspect/install sensors for, etc.
Vehicle Systems (Passive) Other Systems	Vehicle Structural "Complexity", Robustness and/or Materials Level of IVHM Utilization	Large/complex structural forms will have higher stress, more nook/crannies to inspect/install sensors for, etc.
Propulsion Systems (Passive)	Tank Structural "Complexity", Robustness and/or Materials Number of Propellants/Hazard Potential Potential for Propellant Leakage/Accumulations Level of IVHM Utilization	Large/complex structural forms will have higher stress, more nook/crannies to inspect/install sensors for, etc. Number of propellants increases number of labor hours
Vehicle Systems (Active)	Thermal Protection System Number/Diversity of Subsystems Loading on Landing Gear Level of IVHM Utilization	Maintenance of Active TPS, if required, will drive related O&M labor Number/Diversity of Subsystems will drive labor, LRUs, etc. Heavier stresses on landing gears will require higher maintenance
Propulsion Systems (Active) Other Systems	Number/Diversity of Thrusters Number of Propellants/Hazard Potential Level of IVHM Utilization	Number/Diversity of Propulsion Systems will drive labor, LRUs, etc. Number of propellants increases number of labor hours

Table H-1 Vehicle Systems O&M Indicators

THE BASELINE FOR ESTIMATION OF VEHICLE-DRIVEN <u>FIXED</u> O&M COSTS

Ç Adjusted parametric terms are guestimated as:
Propulsion Systems – Active (Primary)
<u>0.14 hrs per flight per pound of vehicle Dry Mass</u>
Vehicle Systems – Passive (Thermal Protection System)
<u>0.14 hrs per flight per pound of vehicle Dry Mass</u>
Vehicle Systems – Passive (Other Structural Systems)
<u>0.11 hrs per flight per pound of vehicle Dry Mass</u>
Propulsion Systems – Passive
<u>0.11 hrs per flight per pound of vehicle Dry Mass</u>
Vehicle Systems – Active
<u>0.08 hrs per flight per pound of vehicle Dry Mass</u>

Propulsion Systems – Active (Other Propulsion)
<u>0.08 hrs per flight per pound of vehicle Dry Mass</u>

Are these values reasonable?

For a 235,000 lb.-Dry Mass Vehicle, flying 50 times per year, they yield @ 0.11 hrs/lb.-flight equivalent to 517 FTE's or a $31/lb. contribution to Cost (@ 40 kbs/launch)

Finally, the specific design features of the concepts should be taken into account: some will have more complex propulsion systems, a greater amount of variation and less robustness in TPS, etc., etc.

The sensitivity of O&M rates to variations in design specifics should be greater in the cases of Active Propulsion Systems and Passive Vehicle Systems (including TPS) <u>and lesser</u> in the cases of Passive Active Vehicle Systems and Passive Propulsion Systems

THE BASELINE FOR ESTIMATION OF VEHICLE-DRIVEN <u>FIXED</u> O&M COSTS

Ç Adjusted parametric terms are guestimated as:

Propulsion Systems – Active (Primary)
<u>0.28 hrs per year per pound of vehicle Dry Mass</u>
Vehicle Systems – Passive (Thermal Protection System)
<u>0.28 hrs per year per pound of vehicle Dry Mass</u>
Vehicle Systems – Passive (Other Structural Systems)
<u>0.14 hrs per year per pound of vehicle Dry Mass</u>
Propulsion Systems – Passive
<u>0.14 hrs per year per pound of vehicle Dry Mass</u>
Vehicle Systems – Active
<u>0.07 hrs per year per pound of vehicle Dry Mass</u>
Propulsion Systems – Active (Other Propulsion)
<u>0.07 hrs per year per pound of vehicle Dry Mass</u>

Are these values reasonable?

For a 235,000 lbs-Dry Mass Vehicle, flying 50 times per year, they yield @ 0.14 hrs/year-lb., equivalent to 16 FTE's or a $1/lb. contribution to Cost (@ 40 kbs/launch)

This is a sufficiently small contribution to overall cost that it will be assumed that this parameter will be estimated at a flat rate:

0.14 hrs per year per pound of vehicle Dry Mass

Lastly, HRST analysis requires a consistent and reasonable treatment of O&M for fixed assets not "close-in" to a particular vehicle concept.

A projection of about 1500 FTE's for the BCS was made earlier.

About $180M/year or about 4%/year of the value of the assets (if they are valued at about $5B)

Rather than estimate labor and other O&M costs separately, the proposal is to treat these costs consistent with current facilities O&M costs experience taking into account increases in automation, sensors, etc., consistent with assumptions regarding the other aspects of the analysis.

Ç Therefore, Infrastructure O&M Costs will be estimated at:
  _ 2% of the Value of the HRST Infrastructure for a Specific Concept
Ç These costs are to be added to find the total recurring cost of any HRST System
Ç For example,
If the capital assets of the general fixed infrastructure are $3B, then the annual O&M costs would be estimated at $60,000,000/year
  _ For a system that launches about 40,000 lbs/launch, this works out to a recurring cost contribution of
    Ç $150/payload-pound if the system supports 10 launches/year
$15/payload-pound if the system 100 launches/year

SUMMARY

The common approach for analyzing HRST operations costs will therefore be:

Ç Infrastructure Fixed O&M Costs will be estimated directly Using:
  2%/year of the Value of the General Infrastructure
Ç Vehicle-Specific Variable O&M Labor will be estimated according to the Table 1
  @ $120,000 per FTE
Ç Vehicle-Specific Fixed O&M Labor will be estimated according to
0.14 hrs per year per pound of vehicle Dry Mass

	Propulsion Systems (Active Primary Prop.	Propulsion Systems (Active Other (e.g. OMS	Propulsion Systems (Passive)	Vehicle Systems (Passive TPS	Vehicle Systems (Active)*	Vehicle Systems (Passive Other
WORSE THAN THE BASELINE	0.21 hrs/flight-lb	0.21 hrs/flight-lb	0.16 hrs/flight-lb	0.16 hrs/flight-lb	0.21 hrs/flight-lb	0.12 hrs/flight-lb
BASELINE (ADV. BS-TYPE)	0.14 hrs/flight-lb	0.14 hrs/flight-lb	0.11 hrs/flight-lb	0.11 hrs/flight-lb	0.08 hrs/flight-lb	0.08 hrs/flight-lb
EASIER THAN THE BASELINE	0.07 hrs/flight-lb	0.07 hrs/flight-lb	0.06 hrs/flight-lb	0.06 hrs/flight-lb	0.04 hrs/flight-lb	0.04 hrs/flight-lb

*Includes the projected inclusion of active cooling as a part of the vehicle in support of the TPS system

Table H-2 Estimation of Variable Vehicle Driven O&M Labor Hours

Following a review of the PrOpHET Tool by KSC, Table H-2 was revised as follows:

	Propulsion Systems (Active) Primary Prop.	Propulsion Systems (Active) Other (e.g. OMS)	Propulsion Systems (Passive)	Vehicle Systems (Passive) TPS	Vehicle Systems (Active)	Vehicle Systems (Passive) Other
WORSE THAN THE BASELINE	0.28 hrs/flight-lb	0.28 hrs/flight-lb	0.16 hrs/flight-lb	0.16 hrs/flight-lb	0.22 hrs/flight-lb	0.22 hrs/flight-lb
BASELINE (ADV. SS-TYPE)	0.14 hrs/flight-lb	0.14 hrs/flight-lb	0.11 hrs/flight-lb	0.11 hrs/flight-lb	0.08 hrs/flight-lb	0.08 hrs/flight-lb
EASIER THAN THE BASELINE	0.07 hrs/flight-lb	0.07 hrs/flight-lb	0.06 hrs/flight-lb	0.06 hrs/flight-lb	0.04 hrs/flight-lb	0.04 hrs/flight-lb

Table H-2 (Revised) Estimation of Variable Vehicle Driven O&M Labor Hours

(See Figure 4, main body of the Report)

In summary, the common approach for analyzing HRST operations costs will therefore be:

- Infrastructure Fixed O&M Costs will be estimated directly using:
  2%/year of the Value of the General Infrastructure
- Vehicle-Specific Variable O&M Labor will be estimated according to the Table H-2
  @ $120,000 per FTE
- Vehicle-Specific Fixed O&M Labor will be estimated according to
  0.14 hrs per year per pound of vehicle Dry Mass

Appendix I - Acronyms and Abbreviations

ACRE	Advanced Chemical Rocket Engine
AAT	Architectural Assessment Tool
COMET	Conceptual Operations Manpower Estimating Tool
COTS	Commercial off the Shelf
ERJ	Ejector Ramjet
ESJ	Ejector Scramjet
ETO	Earth to Orbit
HEDS	Human Exploration and Development of Space
HITF	HRST Integration Task Force
HRST	Highly Reusable Space Transportation
HTHL	Horizontal Take-off, Horizontal Landing
LA	Launch Assist
LACE	Liquid Air Collection and Enrichment
LEO	Low Earth Orbit
MHD	Magneto-hydro-dynamics
MTBF	Mean Time Between Failure
OCM	Operations Cost Model
OMS	Orbital Maneuvering System
O&M	Operations and Maintenance
Ops HITF	HRST Integration Task Force, Operations
OSAMS	Operations Simulation and Analysis Modeling System
PrOpHET	Parametric Operations Hours Estimating Tool
RBCC	Rocket Based Combined Cycle
RCS	Reaction Control System
R&D	Research and Development
RMAT	Reliability Maintainability Analysis Tool
R&M	Reliability and Maintainability
SERJ	Supercharged Ejector Ramjet
SESJ	Supercharged Ejector Scramjet
SPST	Space Propulsion Synergy Team
SSTO	Single-Stage-to-Orbit
TPS	Thermal Protection System
TSTO	Two-Stage to Orbit
VHM	Vehicle Health Management
VTVL	Vertical Take-off, Vertical Landing
VTHL	Vertical Take-off, Horizontal Landing